chapter 3-4

# A/D Example: EMG - Electromyography

## Introduction

Electromyography (EMG) is a methodology central to the study of human movement. It is invaluable for several purposes including, but not limited to:

- Monitoring the timing of contraction of muscles based upon the initiation and ending of the EMG signal during a movement.
- Providing an indication of the force of contraction of the muscle.
- Monitoring the change in the frequency spectrum of the EMG signal as an indicator of fatigue.

The purpose of this chapter is to give some background in EMG and at the same time use it as an illustration of a simple A/D data acquisition and analysis scenario in Kinesiology. Physiologists routinely use custom hardware and software to acquire and analyze EMG signals. However, as will be shown here, we can carry out a lot of EMG analysis using only the facilities of MS EXCEL. In this chapter a simple LABVIEW program will be used to acquire EMG data and save it in an EXCEL data file for subsequent analysis.

## Characteristics of the EMG signal

The EMG signal that we are considering here is derived from surface electrodes. These electrodes will therefore receive all of the signals that are able to make it to the surface of the skin. The surface EMG is simply a product of all of the electrical activity of the cells in the vicinity of the electrodes. In the case of skeletal muscle this is the product of all of the action potentials in the active muscle.

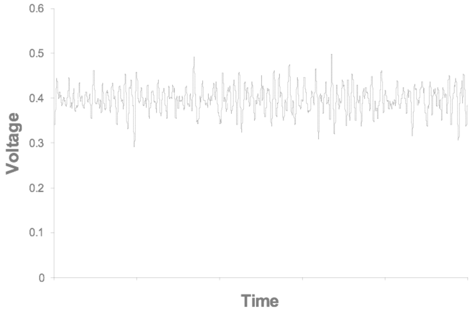


**Figure 3-4.1: Raw EMG Signal**

As you know from your prerequisite physiology courses, the action potential is the sequential depolarization and repolarization of the motor neuron that triggers similar events in the muscle fibre, in order to initiate contraction. A single motor neuron will supply many muscle fibres. The motor neuron and the muscle fibres it supplies are called a motor unit. A motor unit can be composed of 10 to thousands of muscle fibres, stimulated by a single motor neuron, being referred to as small or large motor units respectively. The surface EMG signal that is recorded is a sum of all the action potentials in the muscle below. The amplitude of the EMG signal is referred to as stochastic (random) in nature and can be reasonably represented by a Gaussian distribution function. EMG amplitudes tend to be in the 0 to 10 mV (peak-to-peak) or 0 to 1.5 mV (rms) range.

## DC and AC Measurements

The terms AC and DC were originally used for direct and alternating currents, respectively. But in biomedical measurements DC signal means a non-varying signal, and its frequency is 0 Hz. AC signals vary with time and do not contain 0 Hz. The raw signal that we obtain from electrodes and transducers contains frequencies that can range from a few Hz to many MHz depending on the signal being measured. EMG below 20 Hz usually does not contain any physiological information and frequencies between 0 and 20 Hz are routinely filtered out. EMG is an AC signal, but the equipment can introduce a DC shift called the offset as illustrated in Figure 3-4.2. Such biases are not physiological and should be eliminated by further filters before any further analyses are done.

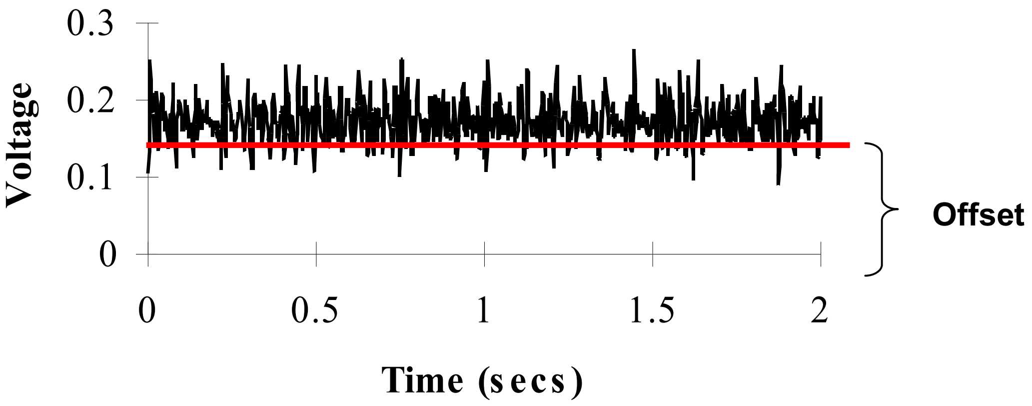


**Figure 3-4.2: EMG will ossilate about a non-zero base line. This shift of the base line from zero volts is termed the offset**

## Frequency Spectrum

The usable energy of the EMG signal is limited to the 0 to 500 Hz frequency range, with the dominant energy being in the 50-150 Hz range. Usable signals are those with energy above the electrical noise level. The specific frequencies contained within an EMG signal can be determined by production of the frequency spectrum. EMG signals as with any other real continuous signal can be expressed as the sum of an infinite number of weighted sinusoids.

$$x(t) = A + \sum_{n-1}^{\infty}[B_n \cos(f_n.t) + C_n \sin(f_n.t)]$$

Where: $A$ *is* any DC component that the signal may have (offset)
$B_n$ and $C_n$ *are* coefficients for the amplitude of each cosine and sine term,
*fn* is the frequency of each cosine and sine term.

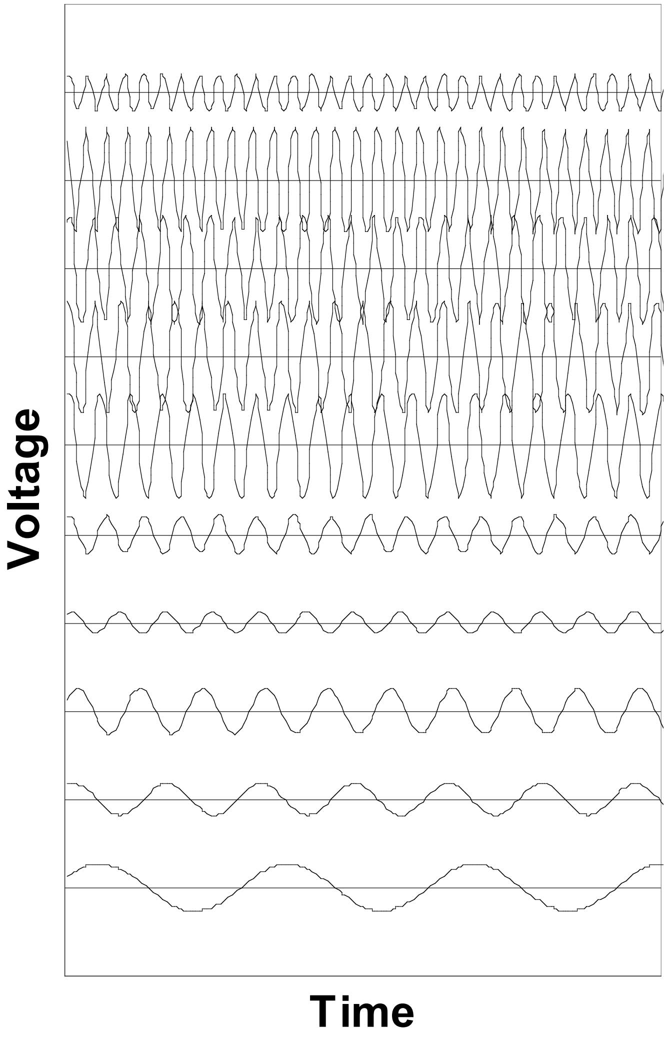


**Figure 3-4.3: 10 individual sinusoids each with different amplitudes and frequencies**

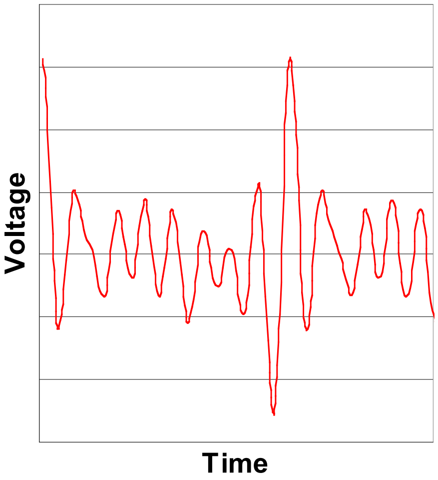


**Figure 3-4.4: Resultant signal produced by summing the 10 signals to the left**

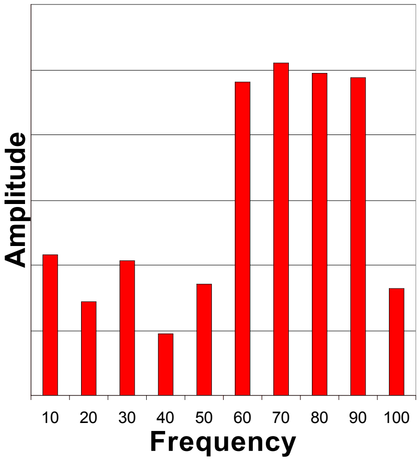


**Figure 3-4.5: Frequency spectrum. Plot of amplitude of signal at each frequency**

This set of sinusoids is called a Fourier Series. By using the mathematical procedure called Fourier transformation the parameters of this Fourier Series can be determined. Figure 3-4.4 shows a simulated signal trace similar in shape to an EMG signal. This signal is actually a sum of the 10 different sinusoids shown in Figure 3-4.3. This is an illustration of the Fourier transformation concept, in that in Fourier transformation, the signal is said to be decomposed into a series of sinusoids derived from the Fourier Series described above. The example here is restricted to 10 sinusoids for simplicity in the example.

The information depicted in Figure 3-4.3 can be alternatively expressed in a convenient fashion by plotting a histogram of the amplitudes for each sinusoid. This concept is depicted in Figure 3-4.5, showing the frequency of the 10 sinusoids on the “X-axis” and their corresponding amplitudes on the “Y-axis”. In this fashion, it is possible to describe the complete set of sinusoids that compose the electrical signal. The original trace shown in Figure 3-4.4 is said to be expressed in the “Time Domain”, since it describes a voltage signal as a function of time. *Figure 3-4.5* describes the same signal in the “Frequency Domain”, since it describes the amplitude of the frequencies contained in it. This type of graph is commonly called a Frequency Spectrum or Power Spectrum. Numerous algorithms and techniques have been devised over the years for extracting frequency information from time varying signals. The most basic and most popular algorithm for accomplishing this task is the “Fast Fourier Transform” or “FFT”.

## Acquiring EMG Signal

EMG signal does have some frequency content at up to 3 KHz. However, most power is below 500 Hz. In fact 300Hz is often used as the upper cut off in a band pass filtering of EMG. The Nyquist frequency is twice the frequency of the highest frequency we want to digitize. Therefore a sampling frequency of 1000 Hz works well for the

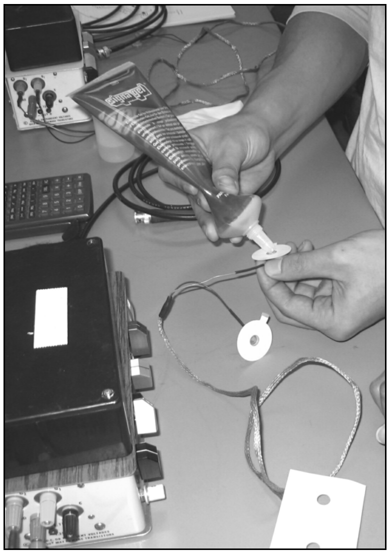


**Figure 3-4.6: Placing gel in the electrode cup**

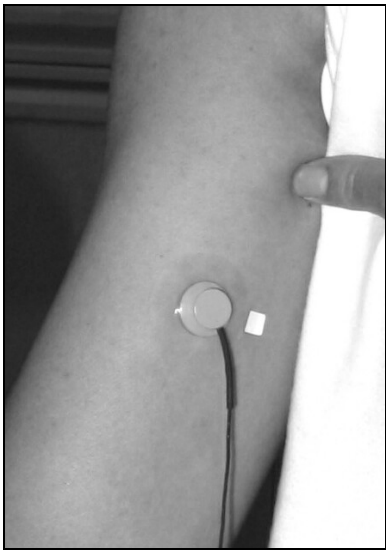


**Figure 3-4.7: Electrode secured with adhesive disc**

EMG where the most valuable frequencies are between 20 and 300 Hz with peak power being between 60 – 100 Hz.

Figures 3-4.6 and 3-4.7 show the preparation and placement of the EMG electrode. The electrode cup is filled with a conducting gel and the electrode is held in place with a double sided sticky disc. The electrode cable may also be taped to the subject to minimize movement artifact from the cable.

As illustrated in Figure 3-4.8 The optimum placement of the sensing electrodes is along the midline of the muscle, between the motor point and the musculotendonous junction, with electrodes parallel with the longitudinal axis of the muscle fibres:

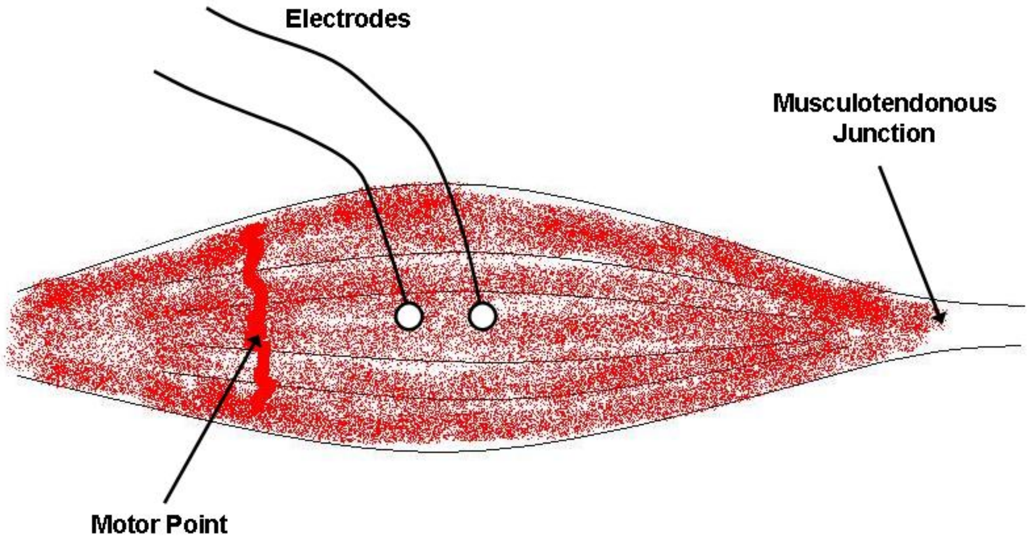


**Figure 3-4.8: Optimum electrode placement is 1 – 2cm apart along the midline of the muscle, between the motor point and the musculotendonous junction, with electrodes parallel with the longitudinal axis of the muscle fibres.**

**Place 1 - 2cm apart –** The distance between electrodes will alter the bandwidth and amplitude of the EMG signal. The smaller the distance shifts The signal shifts towards a higher frequency bandwidth with lower amplitude of the signal. A distance of 1 – 2cm is adequate to obtain a representative sample of the EMG signal from a muscle.

**Midline placement –** Electrodes should be placed away from the edges of muscles where crosstalk from signal of adjacent muscles is more likely to occur. The EMG signal would not then truly represent the activity of the desired muscle.

**Electrode orientation -** The axis connecting the two electrodes should be parallel with longitudinal axis of the.

**Place away from musculotendonous junction** – Near the musculotendonous junction there are less fibers and they are thinner, thus the amplitude of the EMG will be less. The signal also becomes more susceptible to crosstalk from adjacent muscles.

**Place away from the motor point** – Older texts will say place electrodes at motor points (points where minimal electrical stimulation causes a slight twitch of the surface muscle fibers, presumably because of greater neuronal density in this region). Unfortunately, this would challenge signal stability because the action potentials travel distally and proximally along the muscle fibers from the motor point. Because the positive and negative phases of the action potentials (detected by the differential configuration) will add and subtract with minor phase differences there will be erroneous higher frequency components in the resulting EMG signal. An added complication is most muscles have multiple innervation zones throughout the muscle. If you do not have the technology to test for this (surface electrical stimulators) the most judicious location for electrode placement would be in the middle of the muscle between the origin and insertion point

**Ground Electrode Placement:** The ground or reference electrode provides the common reference for the differential amplifier. The reference electrode needs to be placed on an electrically neutral tissue a long way from the detecting electrodes. The wrist (over a bony region) is commonly used (Figure 3-4.9). A large electrode should be used with electrically conductive gel to ensure a very good electrical contact with the skin. This electrode should reduce or eliminate power line interference noise that can be seen if the ground electrode is not in place, or does not have good electrical conductivity with the skin.

**Figure 3-4.9: Large ground electrode placed on wrist with electrode gel to ensure good electrical conductivity**

## Fidelity of the EMG Signal

When detecting and recording the EMG signal, there are two main issues of concern that influence the fidelity of the signal. The first is the signal to noise ratio. That is, the ratio of the energy in the EMG signal to the energy in the noise signal. In general, noise is defined as electrical signals that are not part of the wanted EMG signal. The other is the distortion of the signal, meaning that the relative contribution of any frequency component in the EMG signal should not be altered. The noise may emanate from various sources such as:

**Inherent noise in the electronics components in the detection and recording equipment -** All electronics equipment generates electrical noise. This noise has frequency components that range from 0 Hz to several thousand Hz. This noise cannot be eliminated; it can only be reduced by using high quality electronic components, intelligent circuit design and construction techniques.

**Ambient noise -** This noise originates from sources of electromagnetic radiation, such as radio and television transmission, electrical-power wires, light bulbs, fluorescent lamps, etc. In fact, any electromagnetic device generates and may contribute noise. The surfaces of our bodies are constantly inundated with electric-magnetic radiation and it is virtually impossible to avoid exposure to it on the surface of the earth. The dominant concern for the ambient noise arises from the 60 Hz (or 50 Hz) radiation from power sources. The ambient noise signal may have an amplitude that is one to three orders of magnitude greater than the EMG signal.

**Motion artifacts -** There are two main sources of motion artifact: one from the interface between the detection surface of the electrode and the skin, the other from movement of the cable connecting the electrode to the amplifier. Both of these sources can be essentially reduced by proper design of the electronics circuitry. The electrical signals of both noise sources have most of their energy in the frequency range from 0 to 20 Hz.

**Inherent instability of the signal -** The amplitude of the EMG signal is quasi-random in nature. The frequency components between 0 and 20 Hz are particularly unstable because they are affected by the quasi-random nature of the firing rate of the motor units which, in most conditions, fire in this frequency region. Because of the unstable nature of these components of the signal, it is advisable to consider them as unwanted noise and remove them from the signal.

**Electrode stability -** When an electrode is placed on the skin, the detection surfaces come in contact with the electrolytes in the skin. A chemical reaction takes place which requires some time to stabilize, typically in the order of a few seconds if the electrode is correctly designed. But, more importantly, the chemical reaction should remain stable during the recording session and should not change significantly if the electrical characteristics of the skin change from sweating or humidity changes.

## How can the fidelity of the EMG signal be maximized?

It is desirable to obtain an EMG signal that contains the maximum amount of information from the EMG signal and the minimum amount of contamination from electrical noise. Thus, the maximization of the signal-to-noise ratio should be done with minimal distortion to the EMG signal. Therefore, it is important that any detecting and recording device process the signal linearly. In particular, the signal should not be clipped, that is, the peaks should not be distorted and no unnecessary filtering should be performed.

Because the power line radiation (50 or 60 Hz) is a dominant source of electrical noise, it is tempting to design devices that have a notch-filter at this frequency. Theoretically, this type of filter would only remove the unwanted power line frequency, however, practical implementations also remove portions of the adjacent frequency components. Because the dominant energy of the EMG signal is located in the 50-100 Hz range, the use of notch filters is not advisable when there are alternative methods of dealing with the power line radiation.

## Differential Amplification

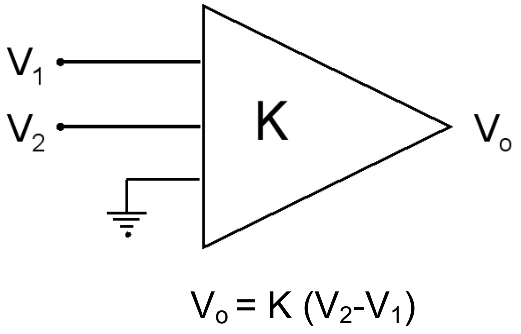


**Figure 3-4.10: Differential amplifier**

In a normal amplifier the output is measured with.respect to ground (zero), $V_o$=K $V_1$, where $V_o$ is the output voltage and $V_i$ is the input. In such a recording only one electrode is used or the recording is said to be single ended. In a differential amplifier (Figure 3-4.?), the output voltage (**$V_o$**) results from the difference between two inputs (**$V_1$ and $V_2$**). With differential recording one uses two electrodes and a ground electrode. Then **$V_o = K(V_2\text{-}V_1)$.** This type of recording minimizes noise. Let us say that there is noise from the line frequency $V_{ac}$. It will arrive at both electrodes at the same time, thus, the noise occurring simultaneously on both electrodes is eliminated.

$$V_1' = V_1+V_{ac},$$

$$V_2' = V_2+V_{ac},$$

$$V_0 = V_2'\text{-}V_1' = K(V_2+V_{ac}\text{-}V_1\text{-}V_{ac}) = K(V_2\text{-}V_1)$$

This assumes that the two signals are subtracted perfectly, which unfortunately they are not. How well your differential amplifier subtracts the two signals is quantified by the Common Mode Rejection Ratio (CMRR). Perfection would be a CMRR of infinity. The higher the value of CMRR, then the better is the elimination of noise. The design of the electrode unit is the most critical aspect of the electronics apparatus which will be used to obtain the signal. The fidelity of the EMG signal detected by the electrode influences all subsequent treatment of the signal. It is very difficult (almost impossible) to improve the fidelity and signal-to-noise ratio of the signal beyond this point. Therefore, it is important to devise an electrode unit that provides minimal distortion and highest signal-to-noise ratio.

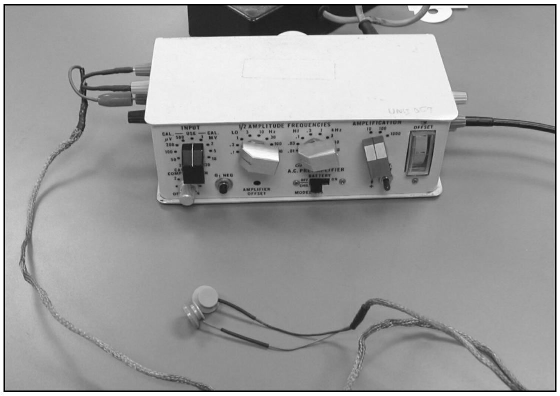


**Figure 3-4.11: Preamplifier with electrodes**

**Figure 3-4.12: Computer acquisition with A/D Board**

**Filtering -** Even with the above considerations, the EMG signal will be contaminated by some noise. The signal to noise ratio can be increased by judicious filtering between 20 - 300 Hz. This filtering is generally accomplished at the amplifier stage using a preamplifier (Figure 3-4.11) before the signal is digitized by the computer (Figure 3-4.12) located outside the active electrode.

## Quantification of the EMG Signal

Common methods used by many in the quantification of the EMG signal are to calculate the Average Rectified EMG and the Integrated Rectified signal. This is achieved by rectifying the EMG signal, and either averaging it or integrating the signal over a specified time interval. This sounds intimidating but it involves very straight forward mathematical processes. You do not need expensive software or detailed computer programming skills. The examples shown in this chapter were calculated using simple EXCEL spreadsheeting commands, from digitized EMG data. Figures 3-4.13 to 3-4 16 illustrate various stages in the analysis of an EMG signal"

Figure 3-4.13: This is a graph of the raw EMG signal collected over 1 second at 1000 Hz. The red line represents the average value of the EMG voltage over the 1 second period. This represents the baseline about which the signal is oscillating and is called the offset.

Figure 3-4.14: The offset has been subtracted from each voltage to produce a signal that now oscillates around a zero volts baseline.

Figure 3-4.15: All the negative voltages are changed to positive, thus all deflections are positive. This is now called the rectified wave form. This can be achieved in EXCEL by applying the absolute ABS()

function. These rectified vales are then averaged to produce the Average Rectified EMG as indicated by the red line.

Figure 3-4.16: The cumulative area under the rectified EMG curve is plotted against time to produce the Integrated EMG.

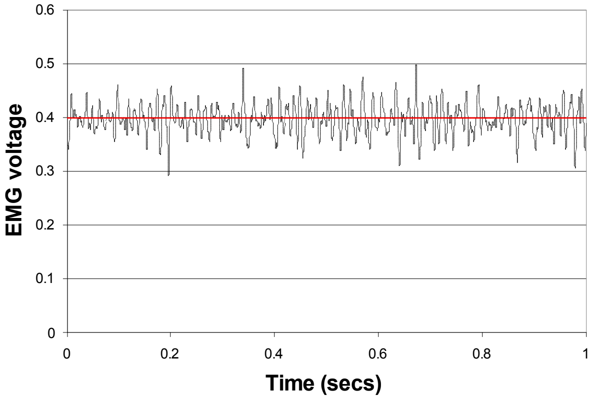


**Figure 3-4.13: Raw EMG. Red line is the offset calculated as average of raw EMG**

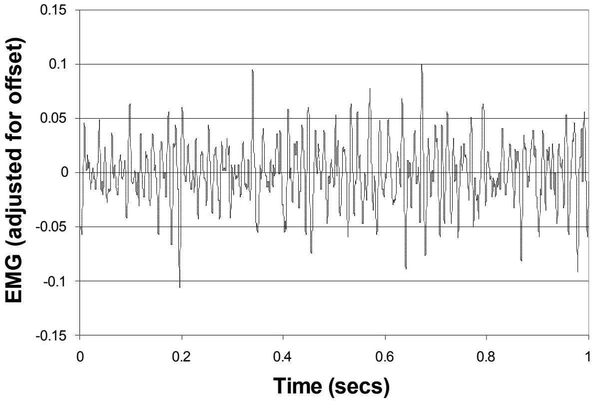


**Figure 3-4.14: Raw EMG adjusted for the offset (voltage – offset)**

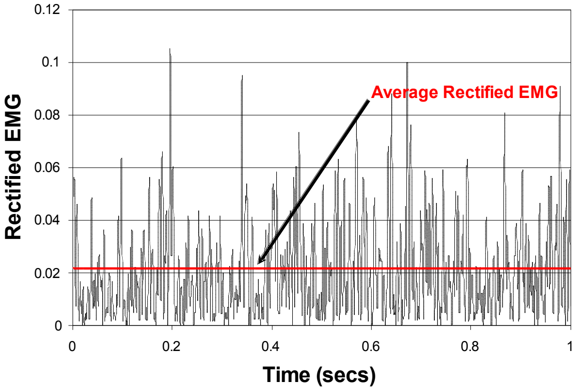


**Figure 3-4.15: Rectified EMG. Red line is the average of the rectified values**

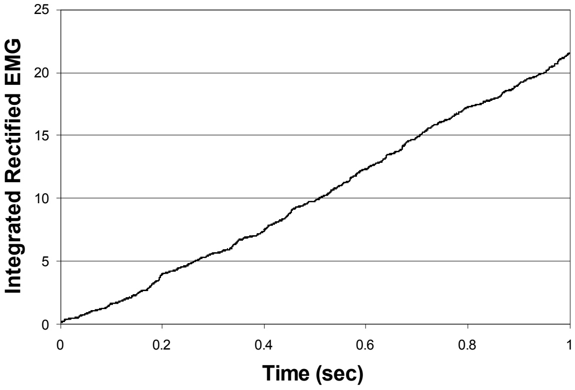


**Figure 3-4.16: Integrated Rectified EMG**

## The Force / EMG Signal Relationship

The relationship between the force produced by the muscle and the amplitude of the EMG signal requires further description. During the past five decades, the scientific literature has revealed an apparent controversy on this issue. Some reports describe a relatively linear relationship, whereas others describe a relative non-linear relationship, with the amplitude of EMG signal increasing greater than the force. In fact, both positions are correct and the controversy is artificial. It is now known that in small muscles where the firing rate of the motor units has a greater dynamic range and motor unit recruitment is limited to the lower end of the force range, the relationship is relatively linear. Whereas, in larger muscles where motor unit recruitment continues into the upper end of the force range and the firing rate has a lower dynamic range, the relationship is relatively non-linear.

The Force/EMG relationship can be investigated with a simple experiment.

**Figure 3-4.17: Holding barbell during EMG recording from the Biceps:**

- Place two surface EMG electrodes over the biceps muscle of the right arm of the subject. Adhesive disks are placed on the electrode and the electrode cup is filled with electrode gel to the level of this disk. The paper backing of the disk can then be removed and the electrodes placed over the belly of the biceps muscle.
- Attach a ground contact plate (with electrode gel) at the wrist of the subject.
- Connect electrode and ground cables to the preamplifier.
- Connect the preamplifier to the A/D panel of the computer, and switch on the preamplifier.
- Start the Labview EMG analysis software.
- Set the acquisition time to 1 sec and the digital filter at low cut off 1 Hz and high cut-off 300 Hz with a sampling rate of 1000 Hz, resulting in a collection of 1000 data points.
- Have the subject hold the unweighted barbell in the right hand with the elbow bent to 90 degrees. This will be regarded as the zero load trial. Initiate a collection run for this position.
- Then initiate 5 more EMG collection runs with 5, 10, 15, 20 and 25lbs added to the barbell. The arm is held still with the elbow at 90 degrees for each of these trials.

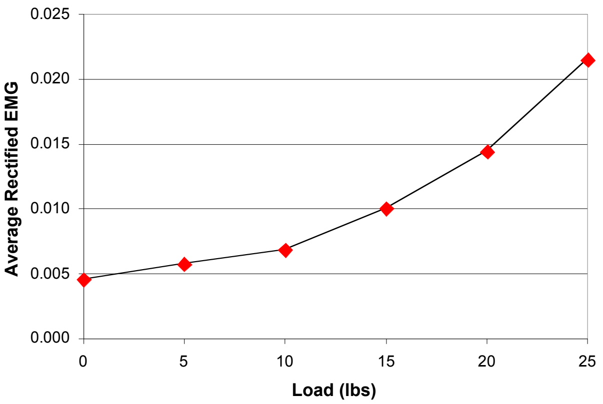


**Figure 3-4.18: Average Rectfied EMG versus Load for barbell experiment**

A typical result of this experiment is shown in Figure 3-4.18. In this case there was a nonlinear relationship between the load on the barbell and the average rectified EMG.

## Moving Averages

One method often used in EMG analysis is to carry out moving (or running) averaging to smooth the signal. It is often applied to the rectified EMG wave form.. The problem is to smooth the data without distorting the biological meaning of the data. The concept of a moving average acknowledges that serial data points are not independent of each other and in fact makes the points more dependent on each other because of the averaging process.

In carrying out moving averaging you simply average adjacent data points to give an estimate to the central point of that group of points. You may choose 3-point, 10-point or indeed any number of points. The number of points however is usually an odd number so that there is an easily identifiable central point. Figure 3-4.19 shows the result of 3-point moving averaging of data. The red line represents the original data. The black line represents the result of the averaging. The moving average serves to lower the peaks and elevate the valleys in the data. The intention is that this serves to minimize noise whilst maintaining the true phenomenon of the data.

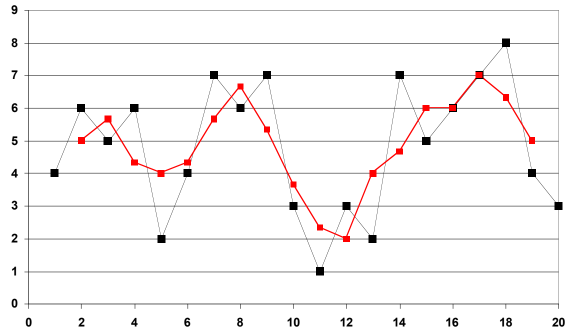
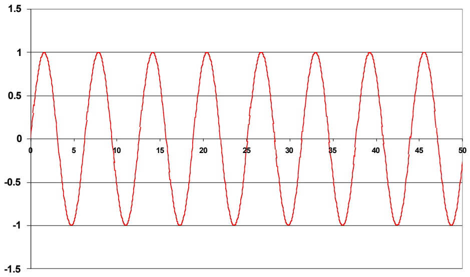
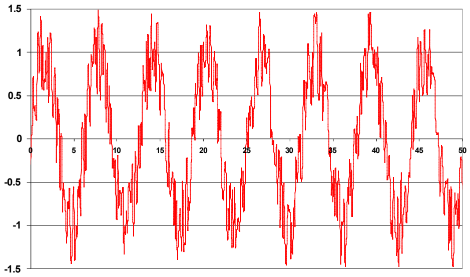


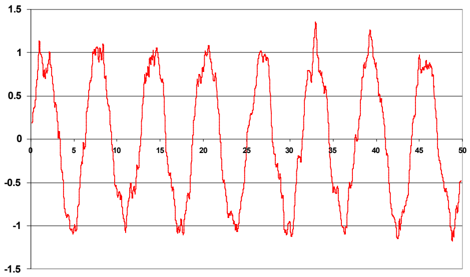
**Fig. 3-4.19: 3-point Moving Average. Black line is the original data. Red line is the result of a 3-point moving average tactic.**



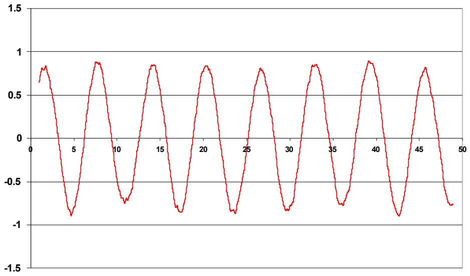
**Simple Sinusoid**



**Simulated Noisy Signal**
**Simple Sinusoid + Random Error**



**5-point Moving Average**



**21-point Moving Average**

**Figure 3-4.20: Comparison of moving averaging tactics on a noisy sinusoid**

One of the problems of moving averages is shown in the four plots included as Figure 3-4.20. Firstly, a simple sinusoid is our initial data, shown in the first plot. To this data was added a random error term to produce the second chart shown to the right here. We will say that this now represents a signal we have collected from some device. It is a sinusoid but it is contaminated with some noise, the effect of which we will try to overcome with smoothing by moving averaging. The next plot shows the result of 5-point moving averaging. Notice that the amount of noise has been reduced and that the waveform still looks similar to the original sinusoid. The last plot is for a 21-point average which has resulted in a smoother curve but unfortunately at the sacrifice of the original sinusoidal information. True the result is a sinusoid with the same frequency but now the resultant curve has less amplitude than the original curve thus the smoothing has altered the original data as well as smoothing out the noise. This exemplifies a problem of moving averages, in that it smoothes out any peaks or valleys in your data, which might be noise but it also might be your valuable signal. A weighted average is an alternative, in that points closer to the middle are weighted more.

**e.g.** **5 data points 10, 9, 13, 12, 1 average = 12**
**with a weighting scheme of 1 3 5 3 1**
**weighted average = [(1x10)+(3x9)+(5x13)+(3x12)+(1x16)]/13 = 11.8**

This will tend not to flatten the peaks and valleys quite so much, since more importance is given to the central points. In the end the decision as to what is the appropriate weighting scheme is arbitrarily based on which scheme will smooth the data but not distort the meaningful part of the signal.