Electromyography: An Introduction
Extracellular Recordings
Fast-Fourier Transformations

Animal Physiology
Spring 2002

Part 1. Extracellular Recordings and Electromyographs:

Electromyography is a technique that enables us to record the action potentials from an entire muscle. The recordings are extra-cellular in nature. It is very much like the ecg recordings that you took several weeks ago -- the procedure in recording them will be remarkably similar.

All skeletal muscle cells transmit action potentials (APs) in a manner similar to neurons. These APs will trigger the events inside of a cell that result in a contraction. In this sense they are similar to the events that we looked at with the heart. However, there are some major differences in cardiac and skeletal muscle. One of the most important is that skeletal muscle cells are not interconnected with each other the way cardiac cells are. They can only be excited by the action of a **somatic nervous system neuron**; each muscle cell is controlled by one neuron, but one neuron may (and usually will) control multiple neurons. The neuron and the muscle fibers it controls are called a **motor unit**.

Each motor unit has a characteristic **innervation ratio** which is the number of muscle cells (muscle fibers) controlled by one neuron. Typically innervation ratios vary from 1 (neuron) : 5 (fiber) for muscles where fine control of movement is needed (for example, the muscles that move your eyes) to 1:300 for muscles that produce very powerful but gross movements (example -- large leg and arm muscles). One other characteristic of motor units is that the cells of each unit have similar force and fatigue characteristics. In class we will soon learn that different muscle cells are grouped into different types (with names like SO or FG) and that these types have different contraction characteristics and different susceptibilities to fatigue. All fibers within one motor unit are pretty much the same. However, different motor units are not the same[1].

All muscle cells within one motor unit become active at the same time. By varying the number of motor units that are active, the body can control the force of the muscle contraction. The process of adding more and more fibers to a contraction is called **recruitment.** We will see examples of recruitment both by looking at emgs and also by looking at force production.

The Nature and Recording of EMGs

EMGs are quite different in appearance from the intra-cellular recordings of action potentials that you have probably seen of neuron action potentials. Typical single cell neuron or skeletal muscle cell APs look like this (see top of next page):

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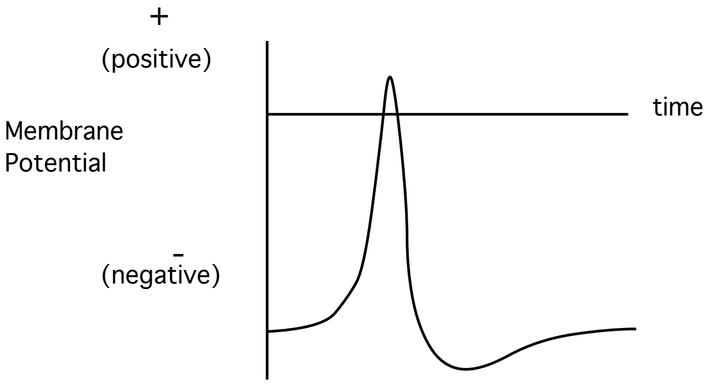
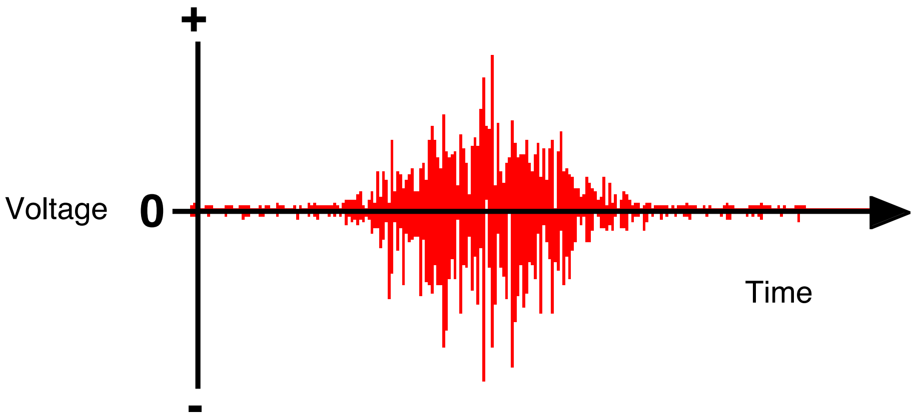
[1] Motor units are entirely one fiber type -- FG or SO -- they are not mixed. Moreover, not all FG and SO fibers are exactly the same and so there are many different SO or FG motor unit types. More about this later in class.



By contrast, emgs will look more like this:

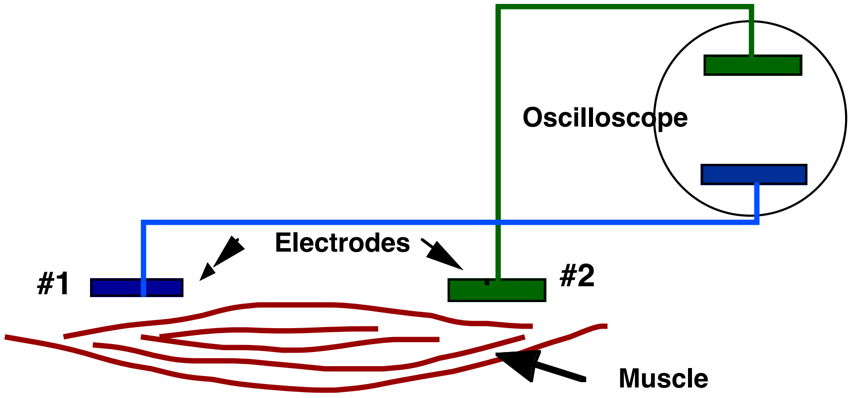


The reason for the difference has to do with the fact that the emg is non-specific -- it records from many cells at once. Thus, electromyography is a technique that enables us to record the action potentials from an entire muscle or from relatively large portions of it. We refer to the signal as a **compound extracellular potential**.

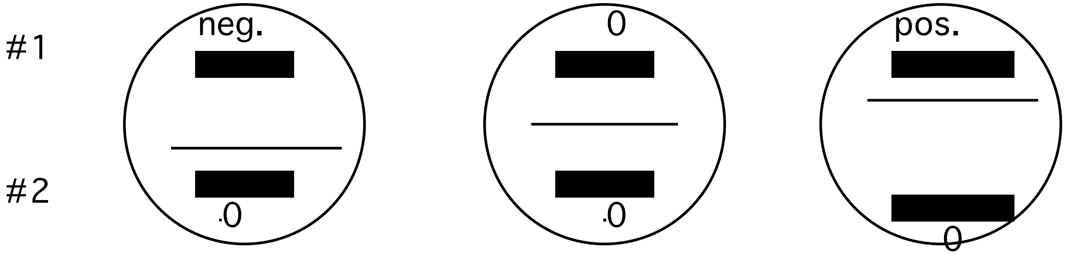
The basic principles of extra-cellular recordings are as follows:

i) Imagine a single muscle cell. When it is stimulated by its motor neuron, it produces an action potential (AP) that will eventually trigger a contraction. In skeletal muscle, this AP is similar to the AP of a neuron, except that its events last a little longer (maybe 5 to 10 msec. instead of the 2 or 3 msec. common in neurons).

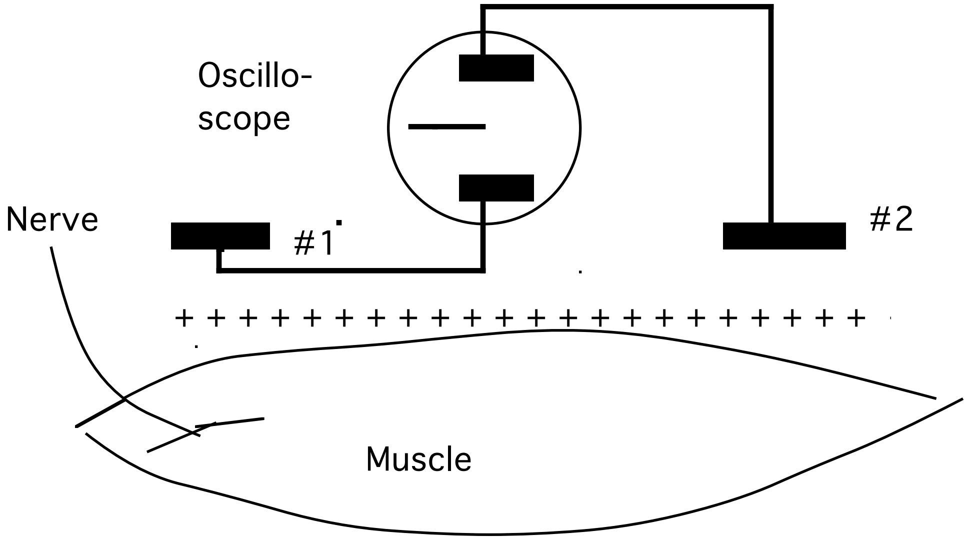
ii) Suppose that we have a pair of electrodes outside of the muscle cell as depicted below:



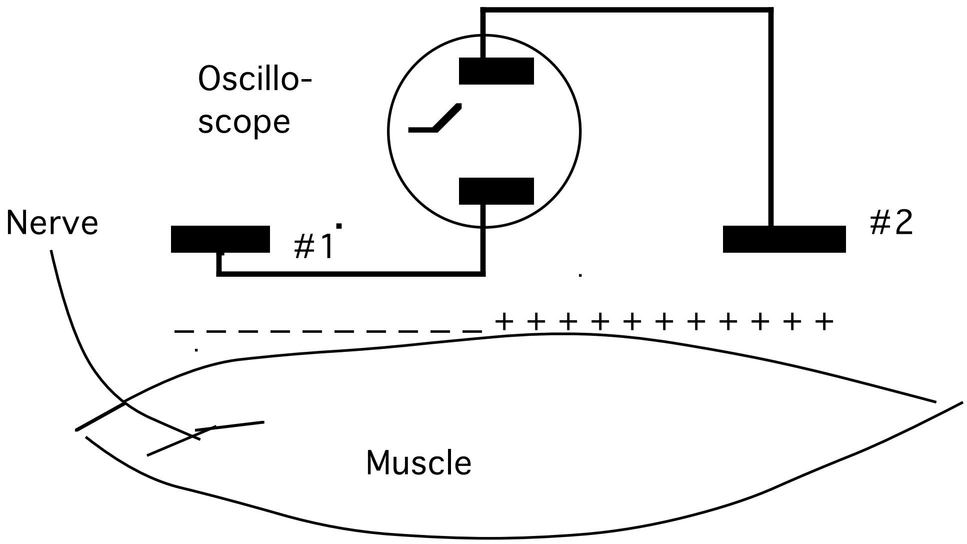
Assume that these electrodes are attached to amplifiers. The amplified signals go to two "deflection plates" in the oscilloscope. In this particular arrangement the #1 electrode is wired to the lower vertical deflection plate. Thus, if electrode #1 is more negative than #2, the oscilloscope's electron beam will be deflected upward; if they are equal there will be no deflection; and if #1 is positive relative to #2 the deflection will be downward:



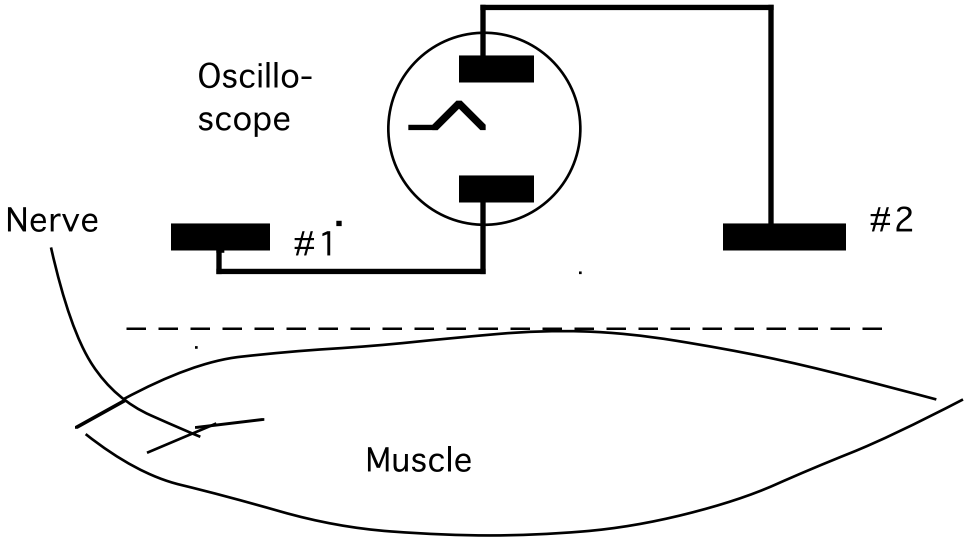
iii) When the cell is resting, the outside of the muscle cells are everywhere a constant positive value relative to the inside. There is no potential difference between either of the extra-cellular recording electrodes (since both see the same conditions) and the oscilloscope records a flat, 0 mV potential signal:



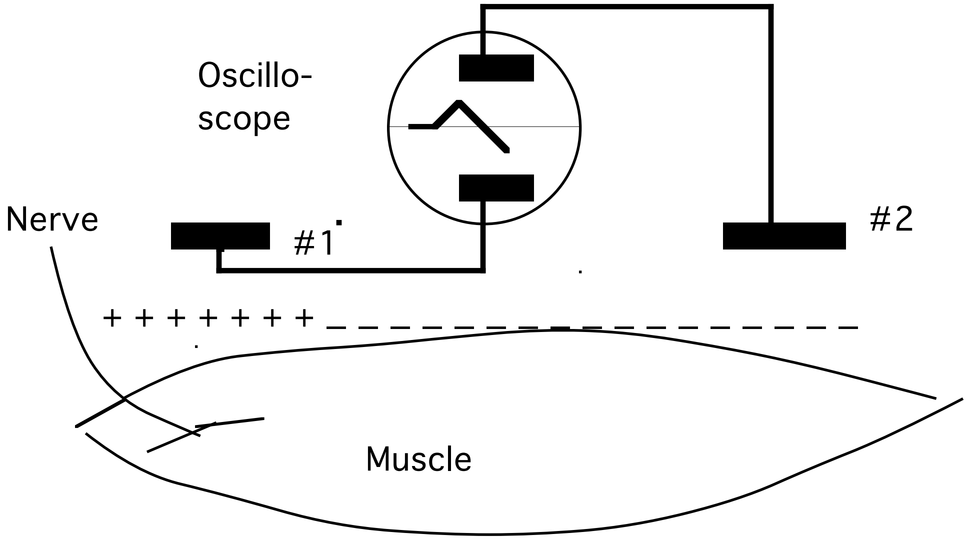
iv) Now, suppose an action potential is generated at the neuro-muscular junction and it begins to move from left to right. As soon as AP generation begins below electrode #1, a potential difference exists between electrodes #1 and #2. This is because the membrane below electrode #1 is now more negative (less positive) than before. (You will learn more about the reasons for this later in the semester). Thus, a negative potential difference is recorded. Notice that the deflection is downward because of the way the electrodes are connected (see discussion above). As the AP builds (the cell depolarizes further) this difference becomes greater and greater, as long as an action potential is yet being generated under electrode #2.



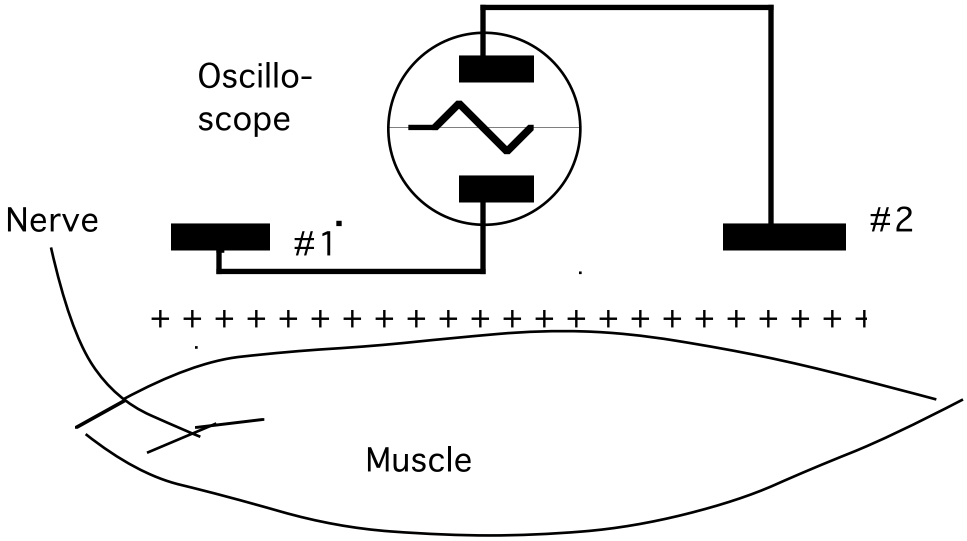
v) A moment later, the AP is being generated under both electrodes #1 and #2. As this happens, the potential between the two electrodes starts to decrease since the outside of the cell under both electrodes is to some degree more negative than at rest. A time will come briefly when both electrodes are of the same value again (not necessarily when both are depolarized to a maximum value -- they only need be at the same voltage as would occur when one is repolarizing the other depolarizing). This situation and the recorded trace up to is depicted below (next page):



vi) As time continues, the depolarization under electrode #2 continues while under electrode #1 the cell is repolarizing or has completely repolarized. During this entire period of time the recorded trace is negative since the #2 electrode is negative relative to the number #1 electrode:



vii) Finally, as the cell repolarizes under electrode #2, the potential difference between the two electrodes returns to 0 mV and the total trace is as is shown:



The general shape of extra-cellular recordings of this type is characterized as being **biphasic** since it has marked positive and negative components. **In general, any time both electrodes are on the same side of the membrane, a biphasic recording will result**.

viii) **Real situations are more complex** since extra-cellular electrodes are over **many, not just one cell**.

(a) Each cell generates its own AP.

(b) Furthermore they are not necessarily in **phase** with each other.

(c) Some may fire multiply while others fire only once.

(d) Also, there is the matter of cell size -- larger cells generate a larger signal. Although it is true that all fibers have APs of similar amplitudes, larger cells produce greater total current flows and their signals posses greater power and are relatively less attenuated with distance. Thus, if these cells are active they can contribute more to the shape of the AP than small diameter muscle cells.

(e) Finally, ***the position of the electrodes relative to different muscle cells also influences the exact shape of the record***.

The result of all of the summation (constructive or destructive) by the electrodes is the production of a compound AP whose exact shape, duration, and amplitude depends on the time over which various fibers contract, the total number of each type of fiber involved and the pattern of their involvement:

This seemingly impossible to understand record can yield much valuable information. Several EMGs may be taken at once to yield the onset and cessation of activity of different muscles during a complex movement. The signals may be analyzed by a process called **FAST FOURIER ANALYSIS** whereby the repetition frequency of the different signals that make up the EMG may be determined. This allows the involvement of particular fiber groups to be quantified. This will be discussed in the next section.

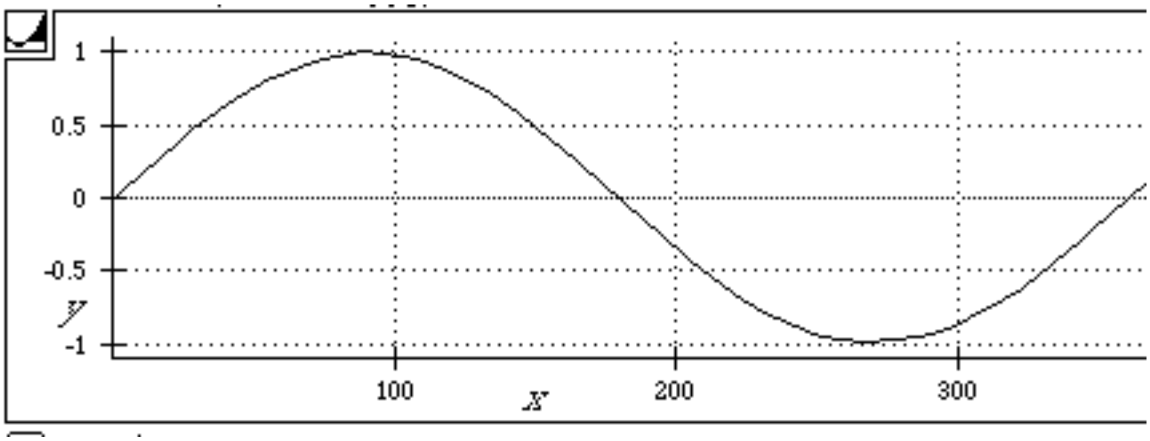
Part 2: Waves, Periodicity, and Fast Fourier Transformations

A. Waves, Sound and Alternating Currents: The salient feature in all of these is the sense of movement, pressure or some other variable reverses (or at least varies) itself on a regular or irregular basis. In electrical circuits this means that current is first pushed in one direction and then the opposite (such that electrons may appear to vibrate around some mean location). In sound the equivalent is that the direction in which an air particle moves reverses itself with the result being that molecule vibrates around some mean point. With extracellular recordings of excitable cells, we see the summed record of many such alternating electrical signals -- one produced by each active cell.

Let's look at the behavior of individual waves and how they add. To keep this simple, we will consider only **waves that vary at regular intervals and which follow a sine function**. In this case, the source voltage (emf) will begin to increase but the rate of that increase will decreasing over time. Eventually, it stops increasing at all and reaches a maximum. It then begins a decrease and then begins an accelerating decrease to zero. After reaching zero, the source reverses and the process repeats itself but this time with the emf applied from the opposite direction.

- The period of time when current comes from either of the two sources is referred to as a **half-cycle**; the entire event where the sources and sinks alternate is a **full cycle**.
- **Cycles** are circular processes and therefore it is reasonable to talk about ***position in a cycle in terms of angle where a half cycle is 180^{o} and a full cycle is 360^{o}.***

Below is a graph of a sinusoidally varying AC voltage for one complete cycle:



where the X axis is degrees and the y axis is fraction of maximum (peak) emf.

(iii) Note that the convention is to assign opposite signs to emfs that come from the two different sources.

(iv) Also note that in the case depicted above, the peak amplitude in the positive direction is at 90^{o} (0.5 π radians) and the peak in the opposite direction is at 270^{o} (1.5 π radians). These angular positions, or for that matter any position within the cycle is (are) referred to as **phase angles**.

c. Mathematically, a generalized version of how emf will vary with position in the cycle uses an equation that gives degrees in radians instead of degrees (recall that there are 2π radians in 360^{o}; that is, in one complete cycle). The equation is:

A1. $V_t = V_{max} * \sin(\frac{2\pi * D}{360})$

where D refers to the angle in degrees.

We need not be concerned with this equation -- it is given for completeness.

d. **Other important definitions**:

(i) **Frequency**: Frequency is an important concept in AC circuits. It is defined as the number of cycles in a second.

(ii) its inverse (the time for one cycle is called the **wave number**).

(iii) The equation for the sinusoidal AC currents that takes into account differing frequencies is:

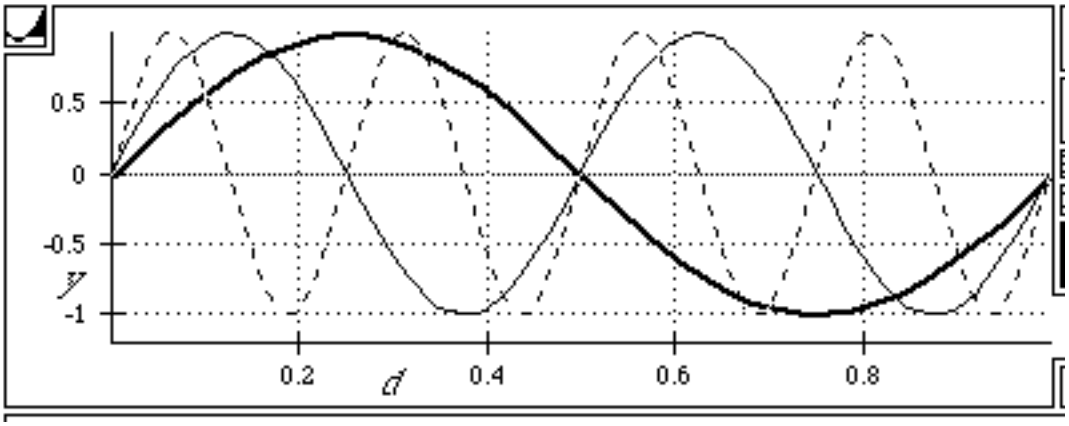
A2. $V_t = V_{max} * \sin\{\frac{2\pi * D * f}{360}\}$

where D refers to the phase angle in degrees and f to the frequency in Hz.

We need not be concerned with this equation either -- it is also given for completeness.

Complex AC waves:

1. The figure below shows sine waves with three different frequencies -- they bear the relationship that each is twice the previous (i.e., base, 2 * base and 4* base).

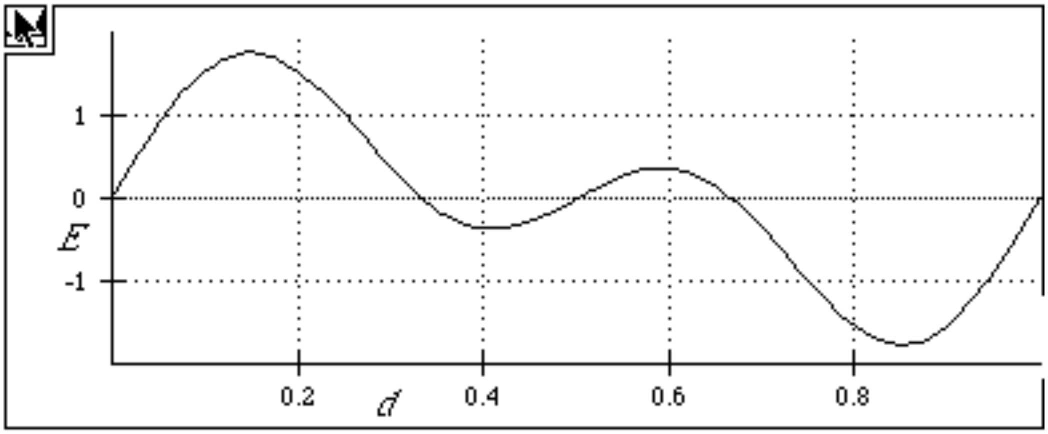


3. **Addition of Waves to Form a Complex Wave:**

a. If several AC current with different frequencies or phase relationships (one starts later than another) are present in the same medium, the resultant is **one complex wave that is the algebraic sum of the component waves**. ***Notice that is exactly what happened when we used two electrodes to measures thousands of APs waves simultaneously in a typical EMG.***

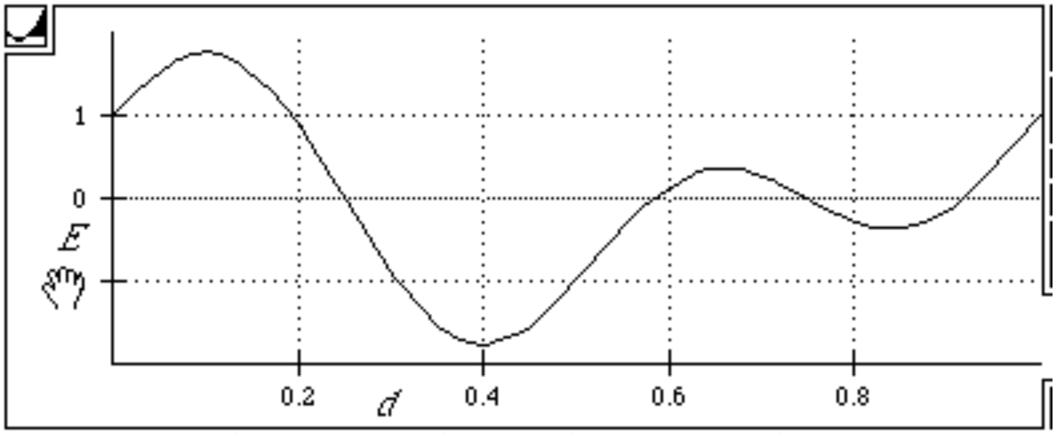
b. In a simple example, let's assume that we have two waves that **start in phase** and **have the same peak amplitude**, but where **one has twice the frequency of**

another (i.e., we have a fundamental and first harmonic). The waveform you would observe in this case would look like this:

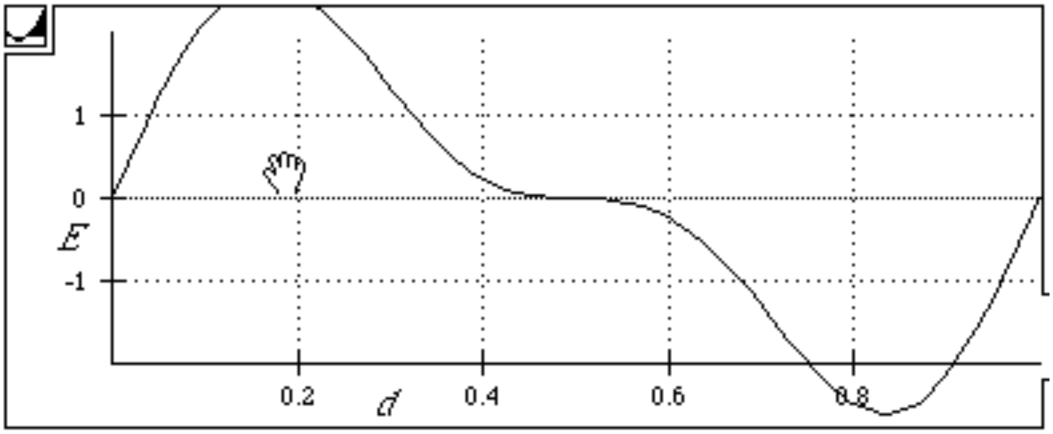


Now for the situation where the two waves have the same amplitude, and one is twice the frequency of the other but where there is a 180° (π radians) difference in phase. Being 180° out of phase means that one wave starts upwards when the other passes through zero.

Draw the two waves that have just been described.



Next for the original two waves, back in phase, except where the low frequency wave has twice the amplitude of the of the wave at twice the frequency. Here is the composite wave:

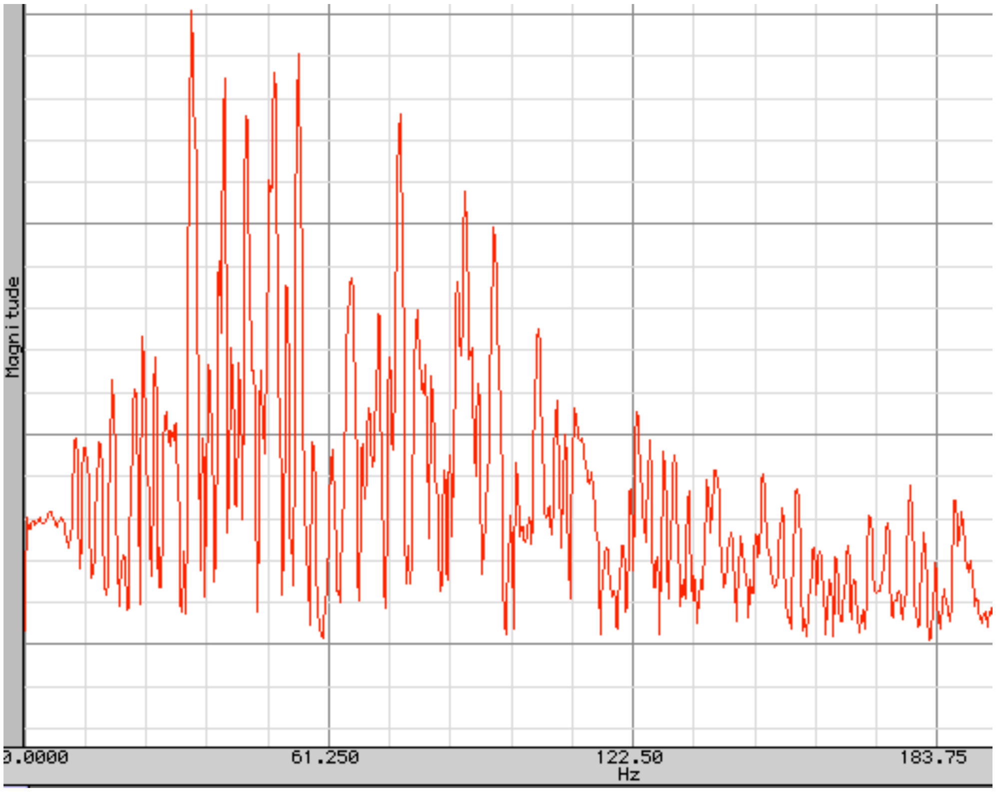


You get the idea!

Fast Fourier Transformation (FFT) Analysis

FFT is an mathematical technique that allows a complex wave to be decomposed into its fundamentals. It can be viewed as the equivalent of applying a number of bandpass filters (see other notes) with non-overlapping frequency ranges that cover the entire range of frequencies thought to be present in a complex signal. If there are frequencies present in a given range, the filter lets them pass. An observer measures their intensity. The resulting data are then graphed as intensity vs. frequency and show up as a series of peaks.

Here is the result of a FFT for the EMG we saw at the start of the last section.



Notice that the Y-axis is intensity (in dB) and the X-axis is frequency. In this case, there were a large number of motor units firing at 33, 45, 55, 55, 75, 90, and 94 Hz with the largest number at 33 Hz.

In lab we will use some data to construct several waves, add them and then analyze the result using FFT.

FFT has many uses both in basic research and in medicine. For example, in neurology, it is important, especially when trying to determine the cause of muscle weakness

Reference

Loeb, G.E. and C. Gans, *Electromyography for Experimentalists* .
University of Chicago Press, 1986.