

ARTICLE

Recording EMG Signals on a Computer Sound Card

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For a few dollars and in a few minutes, a simple circuit can be built to permit a cheap external sound card and a laptop computer to be used as a portable data acquisition system for recording EMG. The circuit uses a common audio amplifier integrated circuit to increase the gain of the EMG signals recorded from EMG surface electrodes and to match the impedance of the electrode-skin interface with

the input impedance of the sound card. Data can be recorded using open source sound editing software and analyzed offline using simple Python code. It is hoped that such activities provide opportunities to undergraduates to gain confidence as experimentalists and as innovators.

Key words: lab activity, signal analysis, noise elimination, undergraduate, neuroscience

Electromyography (EMG) is the recording of the electrical activity of skeletal muscles and is among the easiest forms of electrophysiology to perform and analyze. Because force of contraction correlates with muscle activation, EMG signals can be used to determine how strongly a muscle of interest is activated during different types of movements or under varying resistive loads. EMG can also be used to measure muscle fatigue, as the dominant frequencies of activity in a particular EMG signal tend to shift lower as a muscle fatigues. Finally, EMG can be useful in measuring reaction times, especially when the subject's response is primarily isometric.

Recording EMG is technically simple, typically only involving the application of adhesive electrodes to the skin of the subject and wiring these to a bio-amplifier. Because of its relative simplicity, it provides suitable material to train undergraduates on the idiosyncrasies of electrophysiology: sampling rate, filtering, line noise, impedance matching, analog-to-digital conversion, bit resolution, signal analysis, etc. By providing undergraduates with a simple circuit and maybe a few lines of code, it is hoped that exercises such as these will help undergraduates gain a deeper understanding of the theory and practice of electrophysiology while developing confidence and skills as experimentalists and innovators.

WHY USE A SOUND CARD AS A BIOAMPLIFIER FOR EMG?

Bio-amplifiers range widely both in sophistication and cost, from the Arduino-powered MyoWare system for under \$50 to highly sophisticated clinical research grade systems that include features like online spectral analysis and telemetry. But owing to the size of signals and simplicity of the circuits needed to amplify them, the EMG lab is ripe with opportunities for the garage innovator. Note that much higher quality, but also more complicated, homebrewed EMG equipment has been previously described in this same journal (Matsuzaka et al., 2012).

Homebrewed physiology equipment was once commonplace and is today relatively rare. The benefits of students building their own equipment include increased confidence in electronics development and trouble-

shooting, deeper understanding of how circuits work and what their limitations are, and inspiring further device design and development, related and otherwise.

Previously, I published a paper with two undergraduates who developed a breadboard amplifier that could be used with a computer sound card as a minimal part count EMG recording system (Crisp et al., 2016). The students showed that the simple circuit could be used not only to record electrophysiological signals, but also in conjunction with a webcam to provide an EMG feed synchronized to a video of the movement. They also showed it could be coupled with a smart phone to permit wireless EMG recordings by exploiting common voice-over-IP technologies. What impressed me with these students was that my simple charge of "get an EMG signal on a computer with as few parts possible" launched into a flurry of intensive creative activity; one of these students went on to launch a medical device start-up company for low cost, highly portable diagnostic devices six months after the publication.

While the challenge of using as few parts as possible was interesting, it did not necessarily lead to the most stable and reliable circuit. Using this method in multiple classes, I sometimes observed failure rates as high as 50%, despite the simplicity of the circuit. Here, I present a circuit that accomplishes the same goal with only a few more parts and much more stability and reliability, along with theory of operation and trouble-shooting directions. Notably, 80% of students who have worked with the new circuit have been able to successfully record EMG signals. I suggest that incorporating projects like this into neuroscience teaching laboratories serves both to foster innovation among undergraduate scientists as well as to enhance students' understanding of the principles of electrophysiology. Furthermore, while presenting this circuit as a workshop activity at the FUN (Faculty for Undergraduate Neuroscience) pre-meeting during the summer of 2017, I came to understand that what I had thought to be quite straightforward was less intuitive for potential lab instructors than I had hoped. As such, this article is divided into sections that treat major themes of electrophysiological recording separately to aid the

instructor in teaching electrophysiology theory through this exercise.

THE NATURE OF THE EMG SIGNAL

The surface-recorded EMG signal is a voltage difference that reflects the cumulative electrical activity of numerous muscle fibers (cells) below the surface of the skin. These muscle fibers are organized into motor units, each of which consists of a variable number of muscle fibers under the control of a single motor neuron. A muscle under fine control may be composed of large numbers of small motor units having only a few muscle fibers each, whereas one under coarse control may be composed of larger motor units (Heckman and Enoka, 2012). When an action potential travels down the axon of the alpha motor neuron and invades its presynaptic terminals, acetylcholine is released onto the postsynaptic motor endplates, causing the muscle fiber membrane (sarcolemma) to depolarize to action potential threshold. At this point an action potential is generated and travels toward both ends of the muscle fiber as well as through the transverse tubules that permeate the muscle fiber.

The membrane potential of a muscle cell is largely influenced by the permeability of the muscle cell to chloride at rest. Resting membrane potentials for the sarcolemma can be -70 to -90 mV for skeletal muscles, whereas the potassium and chloride equilibrium potentials are -90 and -95 mV respectively (Hopkins, 2006). Chloride contributes to the maintenance of the membrane potential across the sarcolemma since repeated activation of the muscle can decay the potassium gradient across the membrane. In fact, interstitial potassium can double or even triple during sustained muscle activity in humans (Juel et al., 2000). During an action potential, the membrane potential peaks at +30 mV, such that the action potential has an amplitude of up to 140 mV. While motor units vary dramatically in size, there are a quarter billion skeletal muscles in the human body and less than half a million alpha motor neurons, so the average size, alpha motor unit may contain 500-1000 muscle fibers (Heckman and Enoka, 2012).

When the cells of a motor unit all fire action potentials simultaneously, it gives rise to a relatively large field potential. The parallel arrangement of these large caliber, excitable membranes means that they are in an open-field arrangement, and when the motor unit fires an action potential across each of its muscle fibers, a triphasic single motor unit action potential (MUAP) of relatively large voltage (compared to extracellular field potentials from axons) can be recorded from the surface. The concurrent firing activities of different motor units causes their MUAPs to superimpose in the surface recording, leading to the noisy appearance of the EMG recording for any but the most minimal force voluntary contractions. EMG signals can, for this reason, be crudely modeled using Gaussian noise, scaled by a scalar that indicates the intensity of activation (Fig. 1; Loeb and Gans, 1986; Hayashi et al., 2017).

DIGITALIZATION

Students generally do not understand the principles of

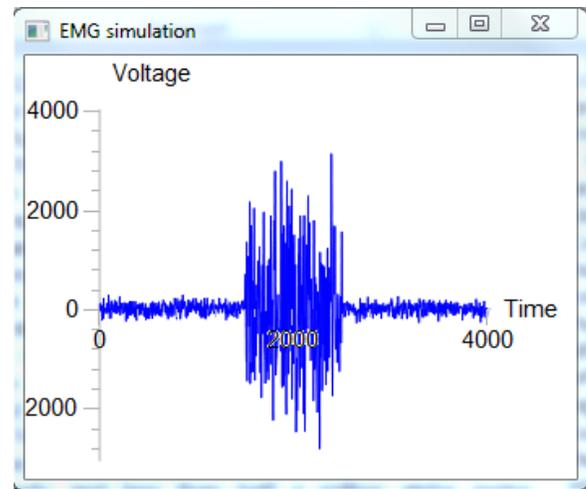


Figure 1. A simple Visual Python simulation of an EMG burst using scaled Gaussian noise.

analog to digital conversion. A good source for issues related to digitalization is Hamming (1997). Surface EMG requires a sampling rate of 1 kHz or higher; signal quality is degraded at lower sampling rates (Ives and Wigglesworth, 2003). Generally speaking, the complex EMG waveform is sampled at a frequency of at least 1 kHz. Because each MUAP has a duration of 10-15 ms, each waveform will be represented digitally as a sequence of at least 10 equally-spaced voltage measurements. Sampling at a lower frequency can lead to signal fidelity problems, especially aliasing. This occurs when the rate of change of the waveform is more rapid than the sampling rate, such that the linear fit between two successive sampled voltages is a very poor fit of the true voltage during that interval. A 10 Hz sine wave, for example, would look like a flat line at a 1 Hz sampling rate, and would be indistinguishable from a 100 Hz sine wave if sampled at 10 Hz, and so on. The cheap computer sound cards that will be used in this exercise to digitalize EMG signals typically have a minimal sampling rate of 8 kHz, which is already overkill for EMG, and they can sample at rates of up to 44 (CD quality) or even 96 kHz (DVD quality).

If sampling rate tells us how closely sampled points will be represented on the time axis, bit resolution tells us how closely they will be represented on the voltage axis. Computer sound cards represent voltages as binary numbers, where an 8-bit value is a unique code that consists of a series of eight ones and zeros. This means that 8-bit binary can be used to represent 2^8 or 256 different values. Most computer sound cards are 16-bit, which can represent 65,536 unique values.

What is the significance of 16-bit sampling for EMG recordings in the current application? It determines the voltage sensitivity of the digitalization. Cheap sound cards tend to have an input voltage range of +/- 10 volts (+/- 400 mV for line inputs on computers). Represented as 16 bits means the minimum sensitivity $20 \text{ V} / 65536$ or 0.3 mV. If an EMG were only 1 mV in amplitude, the minimum sensitivity of the sound card would be 33% of the total EMG signal amplitude. Obviously, this is unacceptable,

and we will need to amplify the raw EMG signal prior to digitalization so that the signal occupies much more of the sound card's voltage range.

IMPEDANCE MATCHING

The bad news about the minimum voltage signal sensitivity gets worse if we consider the resistance of the skin. Impedance is a way of describing resistance with the understanding that resistance will vary as a function of signal frequency. By design, the sound card has an input impedance that is typically 10 k Ω . Much is known about the impedance of skin at frequencies pronounced in EMG because of studies of 60 AC electrical wall currents on the human body during electrocution (Fish and Geddes, 2009). Dry skin can have a resistance as high as 100 k Ω , but the contact resistance varies depending on contact area and other factors.

When recording EMG, we are dealing with two resistances in series (skin and sound card). Two resistors in series make a voltage divider; when a voltage is applied across these resistors, the voltage drop across each resistor is proportionate to the magnitude of that particular resistor. Let's assume that the skin resistance during a particular recording is 10 k Ω . A 1 mV EMG signal would look like only 0.5 mV at the sound card because half of that voltage drop would occur across the skin contact resistance.

A buffer amplifier is a device that matches the impedance of one device to another. In intracellular electrophysiology, the electrode head stage is a buffer amplifier that matches the high resistance of the intracellular recording electrode to the resistance of the electrometer. Buffer amplifiers typically have a unity gain, or even a gain of 0.1x, and would not be appropriate for the EMG application because we need both impedance matching and signal amplification.

An ideal operational amplifier would have an infinite input resistance and an output resistance of zero (although real amplifiers are never perfect). The bigger the input impedance of the amplifier, the more of the EMG signal's voltage is fed to the amplifier. The lower the output impedance of the amplifier, the more of the EMG signal's amplified signal is fed to the sound card. In short, we want the skin resistance to be very small compared to the amplifier's input resistance, and we want the sound card's resistance to be very high compared to the amplifier's output circuit. [For anyone unfamiliar with these general principles, the Axon Guide is highly recommended (mdc.custhelp.com/euf/assets/content/Axon%20Guide%203rd%20edition.pdf)].

In Crisp et al. (2016), we showed that a simple circuit with a minimum number of parts assembled in a breadboard could use a low power operational amplifier to provide impedance matching and amplification and enable recording an EMG on a sound card possible. This minimal parts count circuit, however, was somewhat finicky and required adjustments and fine tuning once assembled. A more stable design was developed that less than doubles the part count. The LM386 is a low power audio amplifier that is ubiquitous in battery-powered audio devices (Fig. 2),

and specifically designed to drive low impedance devices like 8 Ω ear phones. It has a higher input impedance (50 k Ω) than the sound card, but it is far from the infinite resistance we would like. However, it is easily configured for a 200x gain, which will amplify our modest 1 mV EMG signal to 200 mV. This hardly occupies the entire voltage range of the sound card, but the maximum resolution of the voltage is now about 3 orders of magnitude greater than the minimum sensitivity of the 16-bit sound card (~0.3 mV). Better yet, the output resistance is designed to drive loads with resistances as low as 4 Ω , so it is plenty low enough to match our 10k Ω sound card input resistance.

BUILDING THE AMPLIFIER CIRCUIT

The amplifier is quite easy to construct. It is simply just an audio amplifier chip with a handful of extra parts. The LM-386 amplifier does most of the heavy lifting here.

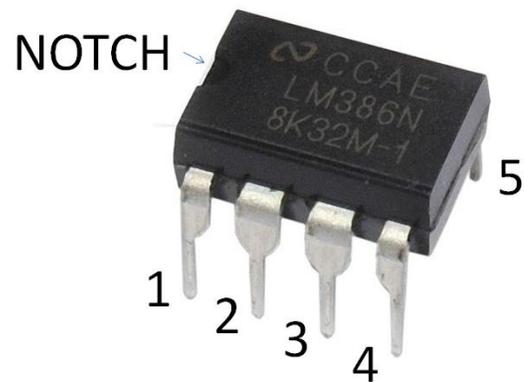


Figure 2. The LM386 integrated circuit is an easy to use audio amplifier that can be used to record EMG on a sound card.

The amplifier has a notch or a dot on one of the two faces that lacks pins. The pins are numbered starting to the left of this notch or dot and proceed in order counter-clockwise around the chip. Pins one and eight are used to modify the gain (volume) of the chip. The gain can be either 20x (if nothing is attached to these pins) or 200x, if these two pins are connected by a 10 μ F capacitor. Pins two and three are the two inputs, which will be configured for use as a differential amplifier. The two skin surface electrodes arranged along the muscle from which the EMG is to be recorded are connected to these two pins by way of ceramic capacitors. It does not really matter which electrode is connected to which pin. Pin four is the ground, and it is connected to four very important points. First, it is connected to the electrode, which might be over the elbow if recording from the biceps brachii muscles. Second, it is connected to the ground plate, a roughly square sheet of aluminum foil, the use of which will be described in greater detail in the "Minimizing Noise" section. Third, it is connected to the negative pole of the 9V battery. Finally, it is connected to the grounded sheath of the connector that plugs into the microphone port on the USB sound card.

There are two additional paths to ground in this circuit. The first is from pin 5, by way of a 10 ohm resistor and a ceramic capacitor in series, such that pins 4 and 5 are essentially connected together via a resistor and a

capacitor. The second path to ground is from pin 6 via an electrolytic capacitor. Again, all the ground points indicated in the circuit are connected to each other, to the ground electrode on the skin, to the negative side of the battery, to the ground of the sound card (as described below) and to the ground plate (aluminum foil). Note that the electrolytic capacitors are polarized, and the positive sides should be oriented toward pins 5, 6 or 8, depending on which pin the electrolytic capacitor is connected to.

Pin five is the output of the amplifier integrated circuit and is connected to the USB sound card by way of an electrolytic capacitor (Fig. 3).



Figure 3. Pin layout of a mono audio connector that plugs into the USB sound card. The tip is connected to the negative end of the electrolytic capacitor whose positive end is connected to in 5 of the LM386 chip. The sheath is connected to the blue rail.

Pin 6 is connected to the positive pole of the 9V battery. The LM386 takes 5V however, so pin 6 will be connected via a 1K resistor. Pin 7 is left open (unconnected).

The entire circuit is illustrated schematically in Figure 4.

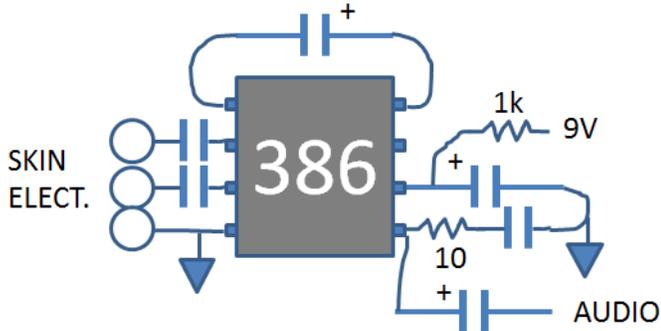


Figure 4. Simplified diagram of the circuit.

The circuit is simple enough to be constructed quickly in a breadboard like the one shown in Figure 5. Working with students (and faculty) new to electronics, it may be important to remind users that the breadboard is divided into two halves by the long trough in the middle. Within each half, each numbered row represents five holes which are electrically connected to each other. The outer edge with the red and blue stripes represents two columns of connected holes, none of which are connected with any of

the rows. Furthermore, the two halves of the board are not connected to each other. These pre-established patterns of connection eliminate the need for soldering. Figure 5 is an example of the circuit connected in a breadboard like the one in Figure 4.

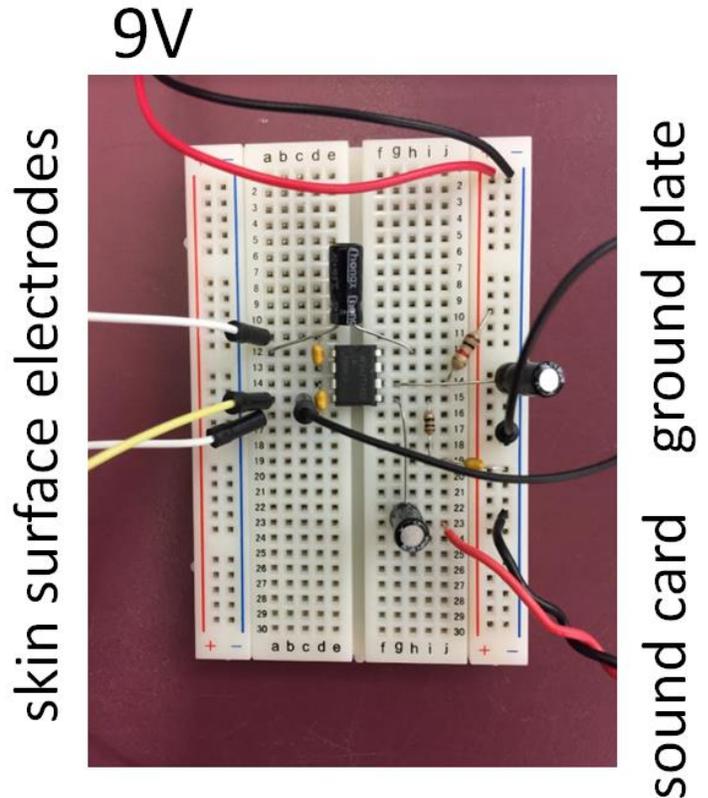


Figure 5. Circuit constructed in a breadboard (prototyping board).

In this image, the LM386 chip straddles the central groove with pins 1 and 8 in the left and right row 12 holes, respectively. Pins 2 and 7 are in row 13, pins 3 and 6 are in row 14 and pins 4 and 5 are in row 15. The electrolytic capacitors (all 10 µF) have their longer, positive leads in rows 12 on the left side (12L), 14R and 15R, and their shorter, negative leads in rows 8R, the blue rail (column) on the right side and 23R, respectively. The ceramic capacitors (all 0.1 µF or #104) have their pins in (a) row 11L and row 13L, (b) row 14L and row 16L, and (c) row 19R and the blue rail. The 1k resistor has its pins in the red rail on the right side and row 14R, while the 100 ohm resistor has its pins in rows 15R and 19R. The two muscle surface electrodes are attached to rows 11L and 16L, and the ground surface electrode is attached to row 15L. A jumper wire is used to connect rows 15L to the blue rail on the right side, and the ground plate (tin foil sheet) is connected to the blue rail on the right side. The plus side of the 9V battery is attached to the red rail on the right side, and the negative side to the blue rail on the same side. The active tip of the audio plug (Fig. 3) is attached to row 23R and the grounded neck of the audio plug is attached to the blue rail on the right side. The audio plug itself is inserted into the microphone jack of the USB sound card. Note that this is not the only configuration with which this

circuit can be constructed and is provided only by way of an example. Those with more electronics experience may want to refer to circuit diagram in Figure 6 before wiring this circuit:

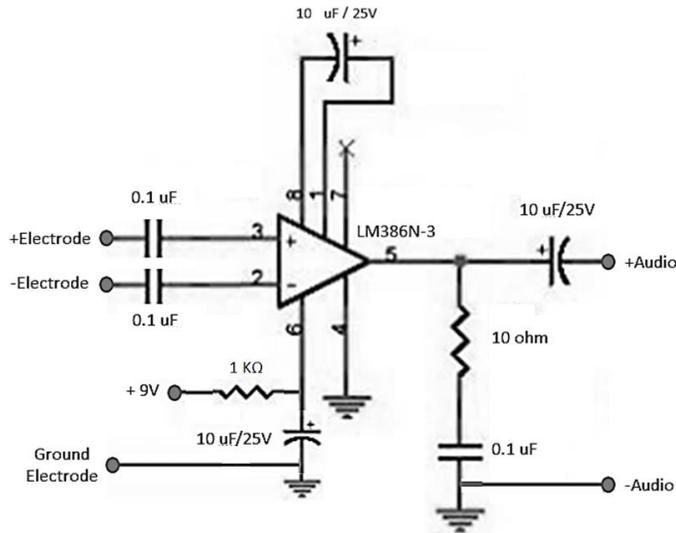


Figure 6. Schematic of the circuit shown in Figure 5.

RECORDING DATA

One of the benefits of using a computer sound card for data acquisition is that there are numerous software packages for analyzing and filtering signals recorded in this method. We have worked principally with Audacity (www.audacityteam.org) because it is platform-independent, free, and has many useful features, some of which will be discussed in the next section. We have also experimented with writing our own custom software for data acquisition and analysis in the Python programming language using the pyaudio and wave libraries. Simple algorithms for removing DC offset, high and low pass filters, notch filters for 60 Hz line noise and plotting power spectrums are not terribly difficult to code, and there are many examples on the web of how to do this in Python.

One important consideration in recording data is sampling rate, especially when writing customized algorithms for signal analysis. As previously mentioned, EMG signals can be adequately sampled at as low as 1000 Hz. However, Audacity defaults to a sample rate of 44.1 kHz (CD quality). We typically turn the sampling rate down to the minimum, 8 kHz, which is still well above the necessary rate for EMG. Sampling rate can be altered using the drop-down menu in the bottom left corner of the Audacity screen (Fig. 7).

When the amplifier circuit has been connected to a USB sound card, this USB sound card is selected as the input. Note that the drop-down menu to the right of the microphone permits selection of a sound acquisition device (the USB sound card, usually). There are actually three microphones on the Audacity user interface. The one to the right with the +/- slider (Fig. 7) controls the amount of volume amplification coming through the acquisition device. This can be adjusted to optimize signal-to-noise by visual inspection. The red circle button (Fig. 7) is the recording button; as soon as this button is clicked, so long

as the device is connected, powered by a battery, and connected to a human, signal should be visible as it is recorded in the signal window of Audacity.

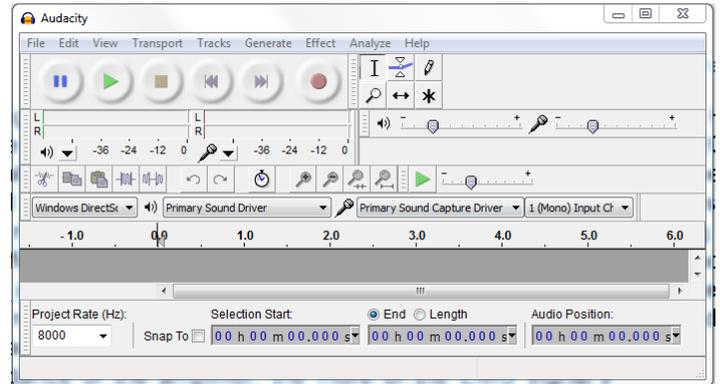


Figure 7. Audacity user interface.

MINIMIZING NOISE

The major downside of do-it-yourself equipment is noise handling. Simple circuits have little or no room for canceling out 60 cycle line noise. Fortunately, there are some simple ways to eliminate noise using this circuit. First, acquiring data on a laptop that is running off of a battery will eliminate the direct connection between the amplifier circuit and the 60 Hz AC power lines that cause so much disturbance. There will still be 60 cycle noise from various proximal radiators, such as fluorescent lights and equipment in the lab space. The grounding plate of aluminum foil reduces this radiated noise considerably. The human subject whose muscles are being recorded from places the ground plate directly against the skin, such as beneath the palm of a hand. When this is done, so long

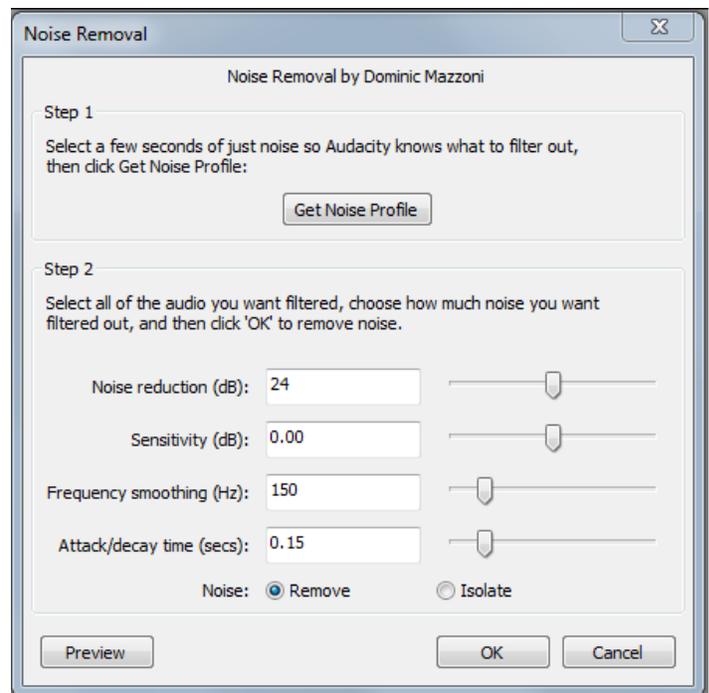


Figure 8. Audacity's "Noise Removal" tool.

as the ground plate is properly connected, the drop in noise is likely to be both instantaneous and dramatic. Note that using the ground plate in this fashion does not increase the risk of an electrical shock; with the laptop on battery power, this is a very safe and very low noise approach to EMG signal acquisition.

Finally, software can be used to eliminate noise. Audacity has, among its many features, a noise removal algorithm (under the effects menu; Fig. 8) that can eliminate noise in signals that have already been recorded. This is done by selecting a few seconds of background noise (when no EMG signal should be present) and then within the “noise removal” function clicking the button “get noise profile” (step 1). Once Audacity has analyzed the noise profile in memory, the noise removal function can be applied (step 2) to the entire recording. Figure 9 shows how dramatic (and disconcertingly effective) Audacity’s noise elimination function can be. Another noteworthy free software package for processing this type of signal is Backyard Brain’s Spike Recorder application (www.backyardbrains.com).

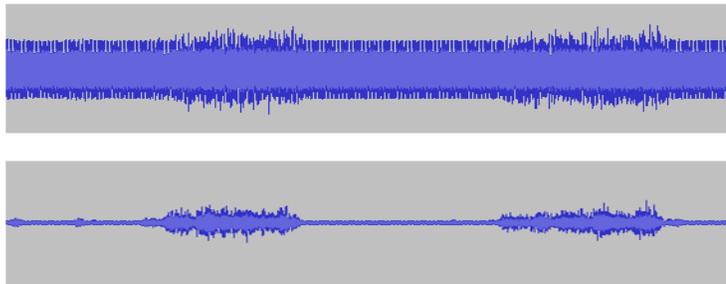


Figure 9. Noisy signal before (upper) and after (below) using Audacity’s “Noise Removal Tool.”

DATA ANALYSIS

It is fairly easy to construct Python scripts to perform custom analysis of EMG recordings. However, because many python libraries are likely to be involved, it is recommended that users take advantage of the Anaconda (www.anaconda.com) development environment for Python (Spyder) as this package automates the library installation and handling process.

A very easy way to work with audio recordings in Python is by recording the signal in Audacity as a 32-bit mono signal with a sampling frequency of 8000 Hz, selecting the EMG burst you wish to analyze and saving it as a .wav file format. To plot a raw EMG recording obtained in this fashion, the following Python 2.7 code works well:

```
import numpy as np
from scipy.io.wavfile import read
import matplotlib.pyplot as plt

rate = 8 #kHz
char = 4 #per 32-bit frame

emg = read("emgburst.wav")[1][::rate]
emg = emg - np.mean(emg)
time = np.array([i/char for i in \
    range(0,len(emg),1)])
```

```
plt.plot(time, emg)
plt.locator_params(axis='x', nbins=10)
plt.locator_params(axis='y', nbins=10)
yrange = max(emg)-min(emg)
plt.ylim(min(emg)-0.1*yrange, \
    max(emg)+0.1*yrange)
plt.xlabel('Time (msec)')
plt.ylabel('EMG (amplitude)')
```

Figure 10 is an example plot generated from a recording with the filename “emgburst.wav” plotted using the code above.

Note that the amplitude is in arbitrary units. There is also a DC offset that is a property of the sound card hardware. This is eliminated in the code by subtracting the signal’s average (`np.mean(emg)`) from the signal (`emg`).

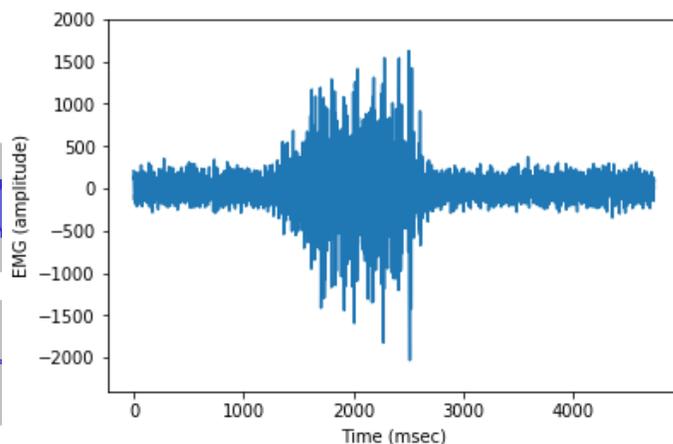


Figure 10. EMG signal recorded using the circuit in the breadboard shown in Figure 5.

The signal can also be rectified (Fig. 11), as is often done, for analysis of the EMG envelop. This is accomplished by inserting the following line prior to the block of code dealing with plotting the graphs (before `plt.plot(time,emg)`):

```
emg = abs(emg)
```

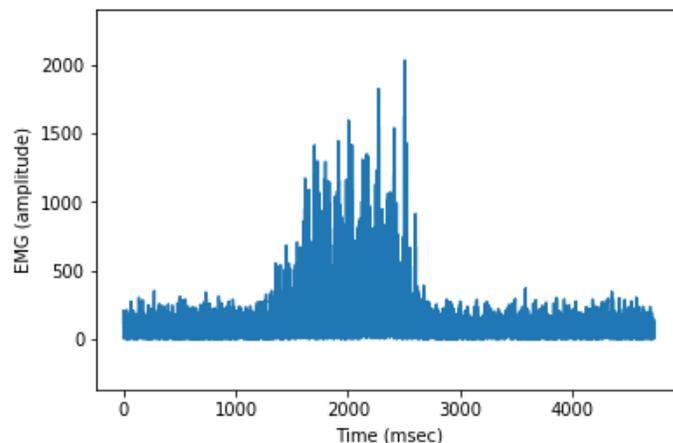


Figure 11. EMG signal from Figure 10, rectified.

Often, such a rectified plot is low-pass filtered so that the envelop is easier to analyze using area under the curve (Figure 12). This code snippet will perform the additional processing by converting frequencies to radians/sec and applying a butterworth filter. It is placed immediately after the line `emg = abs(emg)`:

```
radians = 2*np.pi*rate*1000
nyquist = 0.5*radians
cut_off = 2*np.pi*10 / nyquist
b, a = sp.signal.butter(3, cut_off, /
                      btype='low', analog=False)
emg = sp.signal.lfilter(b,a,emg)
```

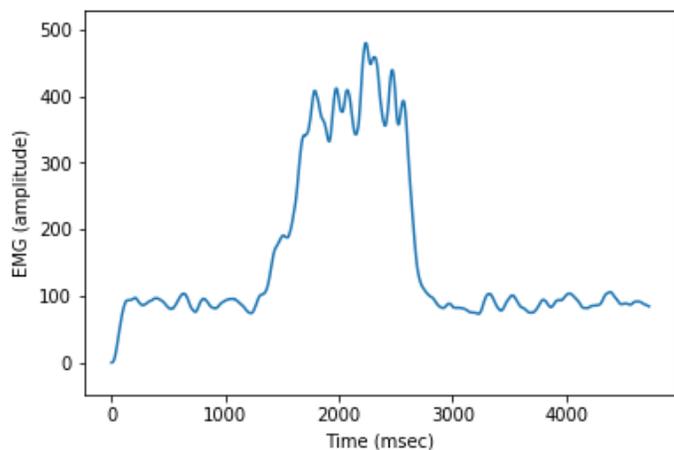


Figure 12. Envelope of rectified EMG signal shown in Figure 11.

CONCLUSIONS

As a postdoc in Ken Muller's lab at the University of Miami, I recall vividly a moment during a lab meeting when we were discussing an experiment that required a single electrode discontinuous current clamp, and my disgust with the price that had just been quoted by a sales rep. Ken simply shrugged it off and said, "Why don't we just build one?" This was an eye-opening moment for me as a scientist. I remember thinking, "Do people still do that kind of thing?" Within a few weeks, I was recording beautiful data from leech neurons using a crude aluminum box with a couple of dials, a switch and a bunch of stickers printed on a label maker. I had learned so much in those weeks about the theory of operation, device design and electronics that I could hardly believe it. We all have moments in our educations that were so big that we spend the rest of our careers trying to recreate them for our students. I hope that by playing with simple circuits and writing little programs, my students too will grow in confidence, ability, and enthusiasm for electrophysiology.

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APPENDIX A: Parts List

- LM386 audio amplifier
- 3 x 10 μ F electrolytic capacitors
- 3 x 0.1 μ F ceramic disk capacitors (#104)
- 1 k Ω resistor
- 10 Ω resistor
- mono audio adaptor plug (see Fig 3)
- 9-volt battery
- 9-volt battery connector
- breadboard
- wire
- wire cutters
- tin foil
- USB sound card
- jumper cables with gator clips
- adhesive surface EMG electrodes

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