

ARTICLE

Breadboard Amplifier: Building and Using Simple Electrophysiology Equipment

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Electrophysiology is a valuable skill for the neuroscientist, but the learning curve for students can be steep. Here we describe a very simple electromyography (EMG) amplifier that can be built from scratch by students with no electronics experience in about 30 minutes, making it ideal for incorporating into a laboratory activity. With few parts and no adjustments except the gain, students can begin physiology experiments quickly while having the satisfaction of having built the equipment themselves. Because the output of the circuit goes to a computer sound

card, students can listen to electrophysiological activity as they see it on the computer screen, a feature many of our students greatly appreciated. Various applications are discussed, including dual channel recording, using streaming media platforms with remote lab partners and acquiring data in the field on a smart phone. Our students reported that they enjoyed being able to build a working device and using it to record from their own muscles.

Key words: electromyography; electrical circuits; remote learning; laboratory exercises; building equipment

Electrophysiology is a critical tool in neuroscience, but the steep learning curve and complexity of the equipment present challenges to student learning in the teaching lab. To train the next generation of neuroscientists requires teaching them to use sophisticated equipment and techniques. Electrophysiology demands an interdisciplinary skill set with some familiarity with topics like membrane biophysics and electrical circuits. Often, significant portions of lab time must be devoted to teaching students how to use the equipment and the software, leaving little time for inquiry-driven learning. Consequently, in order to maximize inquiry (Schwab, 1962; Herron, 1971), many laboratory activities tend to focus on technically simplistic or even “fool-proof” procedures. An alternative approach to easing undergraduates into electrophysiology would be to decrease the complexity of the equipment and use tools of sufficient simplicity that the students can, at least conceptually, understand how they work. We reasoned that once the students comprehend the basic functions of simpler instruments and how to use them to answer scientific questions, they will have the foundation necessary to move on to more sophisticated, modern instruments and techniques. Furthermore, neuroscience has always been an innovative field where questions often exceed the capabilities of today’s instrumentation. For this reason, we felt that introducing students to the processes of constructing instrumentation (and giving them opportunities to be innovative with it) was itself a compelling reason to develop this exercise.

Thus, we developed a minimalist amplifier that could be assembled and used by undergraduates to acquire electrophysiological data in a single laboratory period. With few components, the device can be easily assembled by students in a solder-less breadboard in a short time. Electromyographic data from the device are digitized using a computer sound card, and as such students can see, hear, record and analyze EMG data. Finally, with only one control (the gain), the circuit is both simple and easy to use.

There are other designs for cost-effective and do-it-yourself electrophysiology equipment. For example, the Neuron SpikerBox (Backyard Brains, Ann Arbor, MI) is a relatively simple alternative to high end differential amplifiers that can be built by a novice in an hour or two. The focus of this device is on making electrophysiology equipment affordable and accessible. Matsuzaka et al (2012) published designs for a cost-effective bioamplifier for electrophysiology especially in an undergraduate setting. Electrical Engineer Scott Harden has developed a homebrew electrocardiogram that has a low part count, along with the requisite Python code for noise reduction and data analysis (Harden, 2009). The uniqueness of the current approach is in that we have reduced the number of components significantly and developed methods using widely available software, affording students the opportunity to construct and use their own equipment without custom software. Moreover, the circuit construction can be completed in a very short amount of time (about 30 minutes), leaving ample time for inquiry-based laboratory exercises. In this way, we hope to create an opportunity for the instructor to demystify the instrumentation and promote greater understanding and confidence when doing electrophysiology.

THEORY OF OPERATION

There are many costly items associated with electrophysiology set-ups. One major expense is the analog-to-digital data acquisition system. Generally, these serve as an interface between the bioamplifier and the computer running the software for data capture and analysis. But even low-end computer sound cards are capable of fast digitalization of analog electrical signals. While 10 kHz is adequate for many types of electrophysiological recordings (EMG data is often sampled at just 1 kHz), sound cards have sampling rates capable of at least CD sound quality at a sample rate of 44.1 kHz. Thus, we determined that we could substitute the computer sound card for a data acquisition system.

The typical EMG signal will occupy just a small percentage of the voltage range of the line input to the sound card. Such a weak signal can be amplified by software offline, but this may lead to a poor signal-to-noise ratio. Furthermore, the input impedance of a sound card's line input is typically only 10 k Ω , whereas skin-electrode impedance ranges from <10 k Ω to >100 k Ω . Thus, the skin-electrode interface, in series with the sound card, acts as a voltage divider in which even a relatively low skin-electrode impedance (e.g., 10 k Ω) may result in signal attenuation of about 50%.

The breadboard amplifier serves two purposes. First, it amplifies the EMG signal to take advantage of a greater portion of the dynamic range of the sound card, leading to higher signal-to-noise and better resolution of voltage. Second, it serves as an impedance-matching buffer between the skin-electrode interface and the line input on the sound card; the amplifier's high input impedance and low output impedance significantly reduces EMG signal attenuation owing to the impedance mismatch between the skin-electrode interface and the sound card input.

We chose the Texas Instruments TLC252, due to its low slew rate and high gain-bandwidth product. This two-channel operational amplifier features low power consumption and single voltage supply operation. One

amplifier differentially amplifies the EMG signal and feeds into the second, configured as a variable-gain non-inverting amplifier.

EMG signals typically have amplitudes under 5 mV (often hundreds of microvolts), and a frequency range of 10-500 Hz, with most of the usable energy from 50-150 Hz (De Luca, 2002). Skin-electrode impedance at 100 Hz frequency is about 100 k Ω (Taji et al., 2013), with stainless steel electrodes contributing to interface impedances closer to 75 k Ω and silver-silver chloride closer to 125 k Ω (Okamoto et al., 2014). Thus, a 330 k Ω resistor was selected to achieve a low gain (about 3x) for the differential amplifier (Fig.1, top), but the exact gain depends on the skin-electrode resistance. Note, however, that skin conductivity is variable, between and within subjects. The potentiometer associated with the noninverting amplifier (Fig. 1, bottom) yields a selectable additional gain range of up to 1000x. Depending on the impedance of the skin-electrode interface, total gains of about 10,000x can be expected.

CIRCUIT CONSTRUCTION

Construction of the breadboard amplifier is quick and easy. More detailed instructions and figures are available in the student EMG manual on the author's website (<http://pages.stolaf.edu/crisp>). The necessary supplies are listed in Appendix A. The iMic (Griffin Technology Nashville, TN) or other external sound card is optional; this merely ensures similar performance across computers and minimizes certain problems that can arise with the build in sound card jacks of Apple products. Higher quality external sound cards like the U Control UCA202 from Behringer (Willich, Germany) may permit simultaneous recordings from two different muscles (e.g., antagonistic muscles) using two different breadboard amplifiers on separate right and left audio tracks within the video. It is recommended that instructors solder wires onto the male phone plugs and alligator clips, and short wires onto each of the three pins of the potentiometers prior to lab; for this reason, the soldering station is also listed as optional, as it may not be needed by students or in the teaching lab.

The solderless breadboard is a convenient platform for quick construction and easy modification of simple electrical circuits. Note that the board is divided into two halves, which are electrically disconnected. Within each half, the holes within each numbered row are already electrically connected to each other, but there are no electrical connections between the different rows. Along the edges of the board, there are two long rails typically labeled red and blue. All the holes in these rails are already electrically connected to each other, but the rails are not electrically connected either to each other or to any of the numbered rows.

Step 1. One short wire jumper is used to connect the blue rail on the left to the blue rail on the right.

Step 2. The 8-pin TLC252 integrated circuit (Fig. 2, top) is placed in the board across the midline, such that four pins are inserted in the right most holes of the left hand side of the board while the other four pins are inserted in the left most holes of the right hand side of the board.

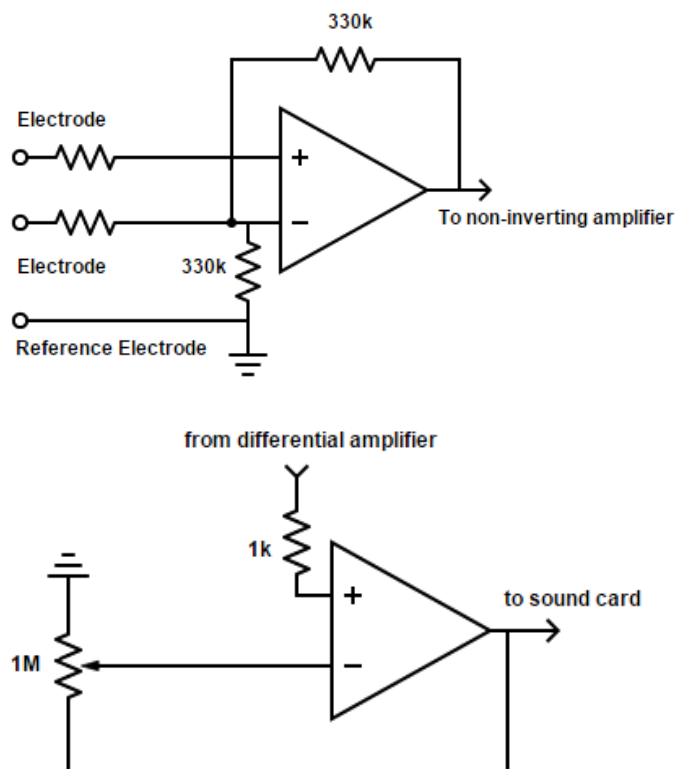


Figure 1. Upper schematic: the differential amplifier and skin surface electrodes that form the front end of the breadboard amplifier. Note that the adhesive electrode pads are represented as resistors, but in reality have a more complex frequency-dependent impedance. Lower circuit: the variable gain amplifier, which amplifies the output of the differential amplifier and is directly connected with the computer sound card.

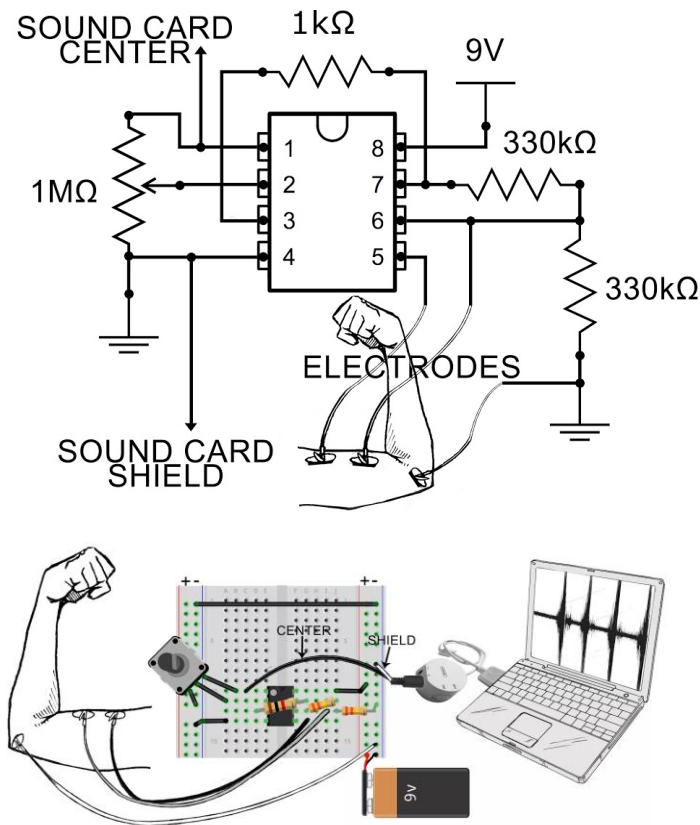


Figure 2. *Top:* Schematic of the breadboard amplifier circuit. The amplifier amplifies the difference in voltage between the electrode leads, which are connected from the electrode pads on the student's arm to the the amplifier. The output of the differential amplifier is passed to the other channel, which is configured as a variable gain amplifier. The final output of the circuit is passed to the computer sound card. Note that the ground electrode on the student's elbow is connected to the negative side of the battery, the ground pin of the integrated circuit, and the shielding of the cable going into the sound card. *Bottom:* Diagram illustrating the breadboard amplifier method. Note that the external sound card is not necessary but is sometimes helpful to minimize differences between sound cards and jacks of different computer models.

Note the position of a semicircular notch on one end of the chip between pins 1 and 8. If such a notch is not present, note the location of circular indentation at one corner of the chip; this indicates the position of pin 1. The pins are numbered from 1 to 8 in the counterclockwise direction.

Step 3. Connect pin 8 to the red rail (Fig. 2, bottom). In other words, if pin 8 is in row 10, put one end of a short wire jumper in row 10 and the other end in any hole along the red rail to which the battery will be connected. Pin 8 is for powering the TLC252. Connect the red rail to the positive side of the 9V battery connector (red wire). Leave the battery disconnected for now, as this circuit is so simple it does not even have an on/off switch. Connect pin 4 to the blue rail. Pin 4 serves as the electrical ground. Connect the blue rail to the negative side of the 9V battery connector (black wire).

Step 4. Pins 5 and 6 are the two inputs for the amplifier on the right hand side of the chip. Connect a length of wire terminating in an alligator clip to each of these pins. The alligator clips will attach to the adhesive electrode pads.

Step 5. A ground electrode is usually also included in an EMG recording configuration. In the case of the biceps, it might be attached to the elbow, near enough that the wire and electrode will be exposed to the same environmental and physiological noise, but far enough away that it will not directly experience the field potentials recorded from the biceps. By placing it over bone, it is not likely to be affected by field potentials from other muscles either. Connect another length of wire terminating in an alligator for the ground electrode to either of the blue rails. We used Skintact adhesive pad electrodes (model 7475; Skintact, Inverness, FL).

Step 6. Connect one 330 kΩ resistor between pin 6 and ground. The other connects between pin 6 and pin 7.

Step 7. Connect a 1 kΩ resistor between pins 3 and 7.

Step 8. The potentiometer has three pins. There is a resistance of 1 MΩ between the two outer pins. The resistance between the outer pins and the middle pin changes as the potentiometer is turned. Connect one of the outer pins of the potentiometer (which should have a short wire soldered to it) to pin 2. Connect the other outer pin of the potentiometer to the blue rail. Connect the middle pin of the potentiometer to pin 1.

Step 9. The breadboard amplifier circuit will interface with the computer sound card through a male 3.5mm phono plug. Connect the wire connected to the tip of the phono plug to output pin one of the TLC252. Connect the wire connected to the shank of the phono plug to the blue rail. Plug the phono plug into the iMic (or other sound card jack).

Step 10. Connect the 9V battery and electrode pads. Note that the lead from the proximal electrode on the biceps goes to pin 5 of the TLC252, while the lead from the distal goes to pin 6.

Construction is now complete. While contracting the biceps, adjust the gain (by turning the potentiometer) until the muscle activity fills much of the Audacity recording track without clipping during peak contraction. The amplifier is now ready to use. Students may have questions about the safety of being connected by wires to the computer. There will be no voltage in the Line In coming from the computer, and 9V batteries do not present a health risk.

SOFTWARE INTEGRATION

Software integration for the breadboard amplifier is simple. Laptops are preferred because recordings have lower noise when running on battery. The use of external sound cards can make it easier to trouble shoot, as students' computers may have diverse configurations with respect to sound cards and mic/line-in jacks. We used the iMic External USB Audio System (Griffin Technology, Nashville, TN), which is a plug-and-play device. It has a switch that allows it to act as a microphone jack or a line-in jack, and the latter is preferable. This is because the line-in setting is meant to work with amplified signals, while the microphone setting is expecting just a microphone with no amplifiers between it and the sound card.

We have found the free Audacity sound editing program (available from www.audacityteam.org) easy to use with

the breadboard amplifier; by default, it both displays the EMG and plays the corresponding sounds while in recording mode. (These software preferences are called “Hardware Playthrough” [Macintosh] and “Software Playthrough” [Windows] in Audacity). In Audacity, the appropriate sound input device must be selected; in our case, this means selecting the iMic USB device as the input. Recording levels should be set to approximately 75% initially, and then increased as needed to see and hear signals.

For the comparisons in Figure 3, a sampling rate of 1000 Hz was selected in Audacity; however, this number was picked only to make the data statistically comparable to that acquired using the default settings for EMG recordings in the iWorx system. Sampling rates of 44.1 kHz or better are possible with most sound cards, which are more than adequate.

There are offline digital filtering features in Audacity that can be applied after data has been acquired (available under the “Effects” drop down menu). The most useful of these are Amplify, Low Pass Filter, High Pass Filter and Notch Filter. The preferred bandpass filtering configuration for EMG is typically 20-300 Hz. However, some muscles (like certain facial muscles) can have components that are faster (500 Hz). Sometimes, a high pass cut off at 100 Hz is applied to eliminate heart rate artifact. At other times, it is sufficient to use a notch filter to specifically eliminate frequencies between 59 and 61 Hz to minimize line noise (60 Hz). Note that no filtering was applied to the raw signals shown in Figure 3A.

Also note that this raw EMG form is not especially amenable to experimental analysis! EMG signals like these are difficult to compare between individuals, and even within an individual as the electrode ages, skin conductance changes or electrode positions are moved. For these reasons, EMG signals are often processed using sophisticated analytics. Audacity has a variety of analysis and processing features that can be applied to EMG signal processing. A common problem with EMG recordings (like that shown in Fig. 3A) is a slight DC offset, often due to something present in the equipment. This can be removed in Audacity using the “Remove any DC offset” option (Effects/Normalize). The same menu option can be used to normalize data, as the scale is not absolute between or even within subjects. Normalization is often set to the maximum voluntary contraction (MVC) level, and the 50% MVC used as a comparison point between subjects. Fourier transforms (see Fig. 3C) can be applied to deconstruct the EMG signal into its frequency components;

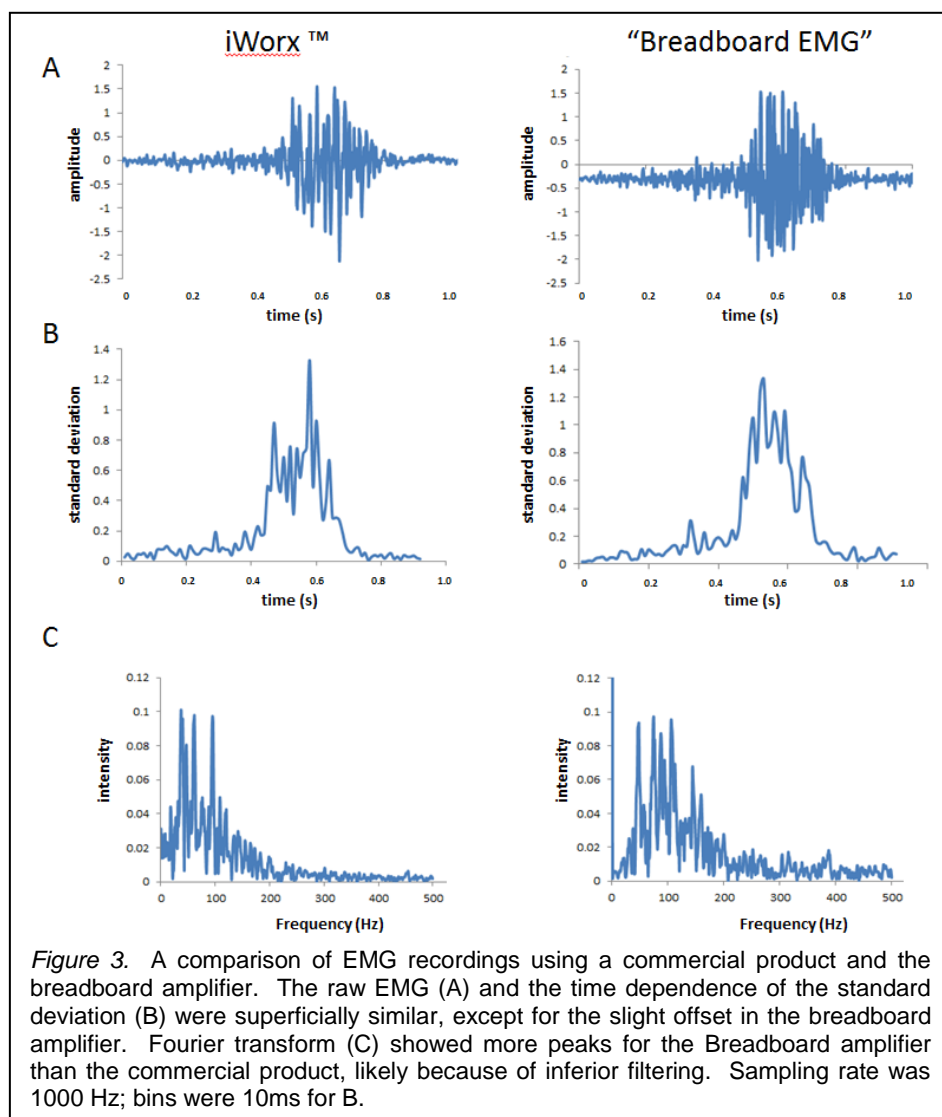


Figure 3. A comparison of EMG recordings using a commercial product and the breadboard amplifier. The raw EMG (A) and the time dependence of the standard deviation (B) were superficially similar, except for the slight offset in the breadboard amplifier. Fourier transform (C) showed more peaks for the Breadboard amplifier than the commercial product, likely because of inferior filtering. Sampling rate was 1000 Hz; bins were 10ms for B.

this option can be found under the Analysis drop down menu and is labeled “Power Spectrum”. For example, during isometric contraction, the median frequency drops with the onset of fatigue. Other common tools for EMG analysis (such as averaging, rectification, integration, RMS and quantification of zero crossings) are not necessarily things that Audacity was designed to accommodate. Audacity data can be exported as text and imported into R, Matlab and other suitable analysis software programs.

Another free and interesting tool that can be used with the breadboard amplifier is the multi-platform software package “Praat” by Drs. Paul Boersma and David Weenink of the University of Amsterdam (www.fon.hum.uva.nl/praat/). Designed for computer-based phonetics analysis, Praat can capture waveforms and has very powerful and flexible analysis tools. Praat also has its own scripting language so it can be programmed to automate certain types of analysis tasks.

A walk-through video of how to use Audacity to obtain, process and analyze EMG signals and a detailed student manual are available from the author’s website (pages.stolaf.edu/crisp).

PERFORMANCE

Amplifiers do not necessarily increase the gain uniformly across all frequencies. To test the frequency-dependence of our breadboard amplifier, we presented the device with a sine wave of approximately EMG amplitude (400 μV peak-to-peak) using a Minirator MR-PRO (NTi-Audio AG, Lichtenstein) and measured the peak-to-peak amplified signal on an oscilloscope. We used 100 k Ω resistors between the outputs of the Minirator and the inputs of the TLC251 to simulate the skin-electrode resistance. We observed the highest gains for signals of frequencies less than 75 Hz, and a steady decline of about 1 dB per 100 Hz above 250 Hz. There was a rather steep drop in gain from 50-150 Hz, with a total loss of about 5 dB over this frequency interval.

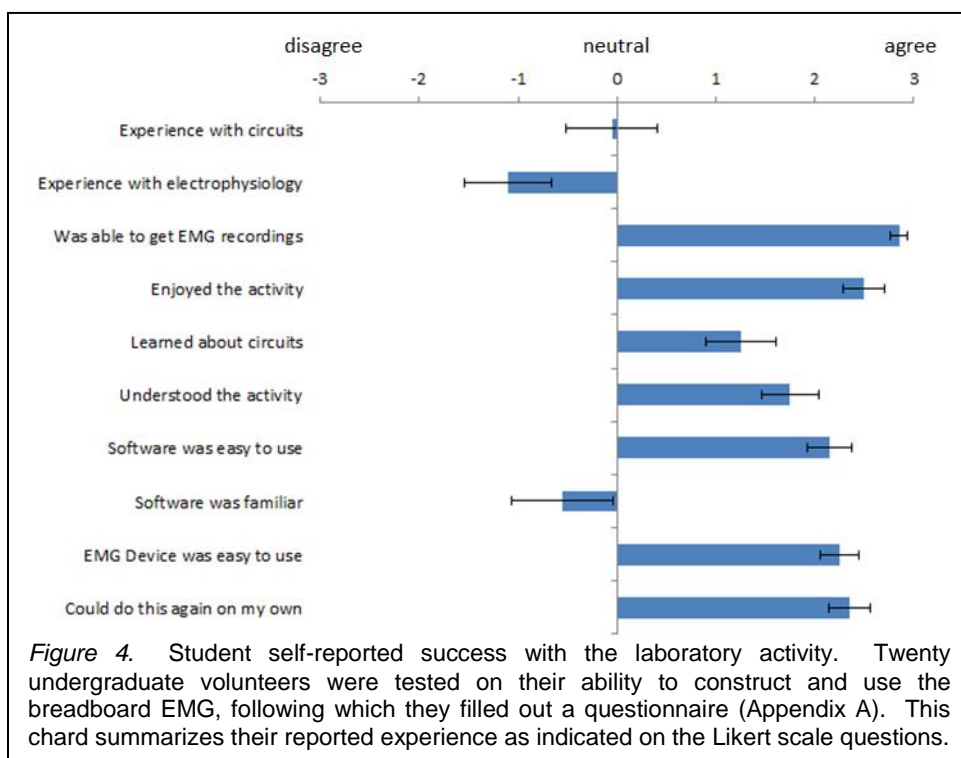
Figure 3 shows a comparison of the breadboard amplifier's performance to that of a commercial product (iWorx; Dover, NH). Two EMG recordings are shown (Fig. 3A), both recorded at a 1000 Hz sampling rate. The commercial product data was captured using the LabScribe 2 proprietary software (iWorx). The breadboard amplifier data was digitized using Audacity. While they were obtained from the same student's biceps brachii using the same electrodes, the two recordings were not simultaneous. The student tried to capture similar looking contractions (with respect to amplitude and duration) using the two different recording set-ups. The amplitude scales are relative; LabScribe 2 displays data in mV but Audacity uses a linear vertical scale (-1 to 1) by default.

The vertical scale of the data from the breadboard amplifier was adjusted artificially to be of a comparable vertical range to the data obtained with LabScribe 2. The breadboard amplifier has a slightly noisier baseline and a voltage offset. The time-dependence of the standard deviation for the two signals is shown in Figure 3B. Fourier analysis of the two signals reveals more peaks and less high frequency attenuation from the breadboard amplifier (Fig. 3C).

THE STUDENT EXPERIENCE

Our students were invited to spend half an hour completing the activity of constructing the circuit, attaching electrodes to their biceps, and seeing and hearing their muscles contract using EMG. The end goal of the activity was to build an EMG circuit that worked, and to record physiological activity.

In order to better understand the student experience of completing the breadboard amplifier exercise, 20 undergraduate students (11 males and 9 females) were asked to complete the exercise individually. St. Olaf College IRB approval was obtained for participation in the



study. As the student participants were on campus for summer research or classes, they represented a diverse distribution of majors. The most common majors were biology (4), psychology (3), chemistry (2) and independent majors (2), but also represented were physics, French, environmental science nursing, math, economics and studio art. Thirteen students were rising seniors, 5 were rising juniors and 1 was a rising sophomore. Nineteen students were able to make the exercise work on their first try. One student could not get it to work initially. However, this student asked to come back and try it again on different day, and on this second attempt, was successful. The amount of time students took to complete the exercise varied, with a range from 20 to 45 minutes to read the directions, construct the circuit and obtain recordings from their own biceps brachii. The mean duration from start to finish was 34.0 ± 2.5 (SEM) minutes ($n = 20$). After completing the exercise, they filled out a questionnaire (see Appendix B).

The students found the device easy to build and use, and generally enjoyed the activity (Fig. 4). They were also comfortable with the software. Forty-five percent of the students needed at least some assistance from the teaching assistant to complete the activity. In their open-ended responses, three students struggled with where and how to put components in the holes on the breadboard, two struggled with the software, and one complained of a lack of familiarity with the names of the parts.

Ten students reported that their favorite thing about the exercise was "hearing" the muscle contractions. Five students said the best thing was being able to build the device themselves, and only two said being able to see the contractions was the best part. One student wrote "It was really cool to do and you get to build your own recording unit. That's cool!" Another said "it's fun, creative and

genuinely interesting for anyone regardless of academic interests.” A third offered that “we don’t have to be chem majors to have general knowledge about what happens in our body. This should be a general knowledge that people should have.” Given the above, we believe that the building and using of the breadboard amplifier was both enjoyable for students and feasible for incorporation into a teaching lab.

FURTHER APPLICATIONS

The breadboard amplifier is also suitable for use with video. Since most computers have built in cameras capable of acquiring video, it is easy to use applications such as Quicktime to record video that is synchronized with EMG recordings. The breadboard amplifier feeds its output into the computer soundcard, so it is simple to acquire a video of, for example, a moving limb with the EMG recording as a sound track (Fig. 5). When the video is played back, the sound of the muscle recordings is synchronized with the movements in the video.

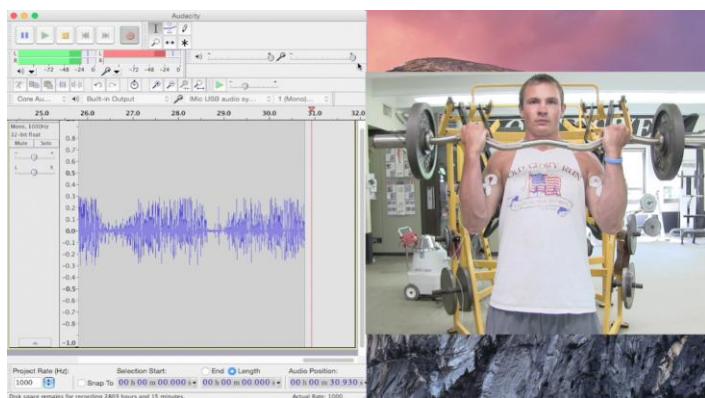


Figure 5. Synchronous display of EMG signals in Audacity (left) during playback of the Quicktime video (right) of a weightlifter doing curls. An audio cable connecting the audio out (from Quicktime) to the audio in (to Audacity) makes it possible to view the EMG recordings in Audacity during video playback.

To visualize the EMG signals during video playback, an audio cable can be attached from the audio out jack (assigned as the output for the video playback program) to the line in jack (defined as the input for Audacity). We call this the “audio loop” technique, but it can also be accomplished using Virtual Audio Cable software (from NTONYX.com). In this way, the video can be observed in one window while the EMG signals are displayed in another on the same computer.

A two-channel version of the device is not much more difficult to construct and use than the single channel version. It does require, however, the use of a stereo input. The iMic has a switch that converts between mono microphone input mode and stereo line input mode; this should be in the line input mode when using two channels. Figure 6 shows a circuit diagram of a two channel version of the EMG circuit (top). The circuit is simply two replicas of the single version supplied with a single 9-V battery. A sample recording from a dual-channel version is also shown (bottom). Each channel is fed by two leads from

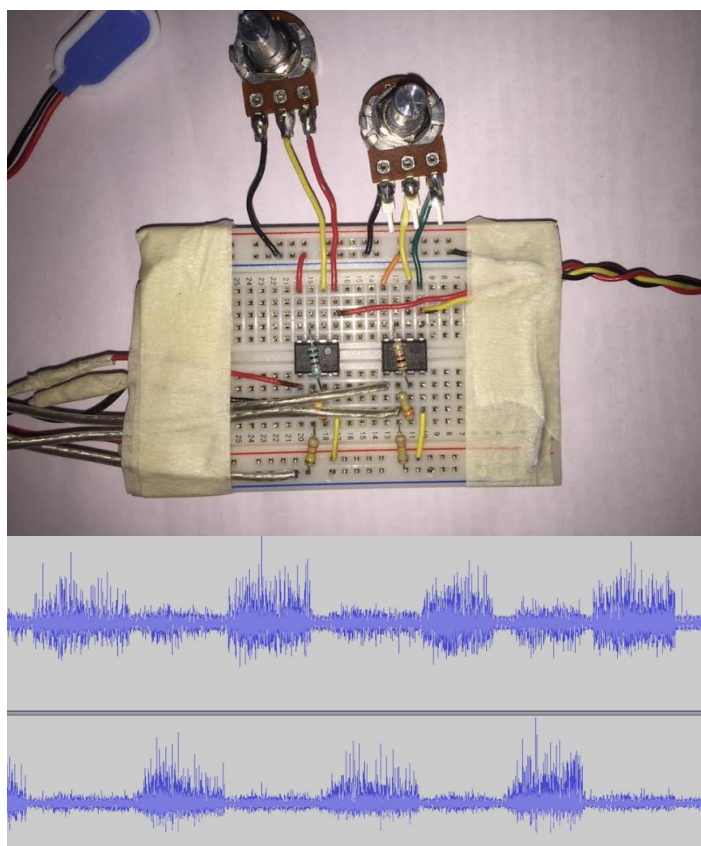


Figure 6. A dual-channel version of the breadboard EMG circuit. Two single channel circuits (each identical to those shown in Fig. 2) can be fed by the same 9-volt battery into the left and right inputs of a stereo soundcard line input (top). Alternating contractions in the flexors and extensors of the left forearm are shown (bottom). Note that there appears to be some bleed-over between the channels, likely due to the proximity of the two recording sites to the ground electrode on the elbow. However, moving the ground electrode further from the recording site resulted in higher background noise (data not shown).

pairs of electrodes located over the extensors and the flexors of the forearm. A single ground is used, and in this case, the ground electrode is placed over the elbow.

Streaming media platforms can also make it possible for lab partners to work together or with an instructor at a distance. We have used Skype and Google Hangouts to stream video of a moving arm along with the corresponding EMG of the biceps brachii to a receiving computer in another location (Fig. 7). The receiving computer displayed the streaming video and used the “audio loop” technique so that the EMG could be both seen (in Audacity) and heard at the other location. While traditional Google Hangouts video chat permitted up to 10 participants simultaneously (without having the business plan for video conferencing), Google Hangouts On Air has (at least in theory) an unlimited number of participants in a single hangout, bandwidth permitting. At a minimum, this makes it possible for multiple students to capture data simultaneously on their own computers without having to send large files over email.

The breadboard amplifier is also amenable to use with tablets and smart phones (Fig. 7). On the iPhone, for

example, the free app Hokusai Audio Editor (Wooji Juice, Ltd., England), while lacking the filtering and analytical features of Audacity, is capable of capturing and displaying EMG data. Alternatively, an iPhone could be used to stream EMG data (using Hangouts, Skype or Facetime) to a desktop computer at another location, where the data was captured, stored and processed. (Note however that iPhone uses a different type of phono plug, and an inexpensive 3.5 mm headphone adaptor plug will be required, such as the “3.5 mm 4 Pos to 2x 3 Pos 3.5 mm Headset Splitter Adapter” from StarTech.com). This type of application might be useful, for example, if data collection required a high degree of mobility. For example, data could be acquired in this fashion wirelessly from a mobile subject, using an iPhone and streaming media to send recordings live to a home base computer. In this set up, it would of course be wise to use a more permanent, soldered system and as short wires (possibly held in place with tape) as possible to minimize movement artifact.

Finally, this circuit is adaptable into other breadboard electrophysiology applications. For example, we have been able to record EKG using this circuit with chest electrodes.

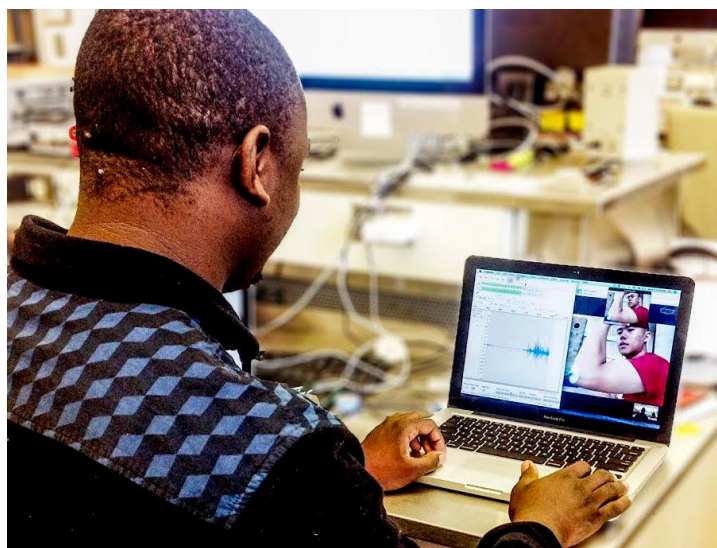
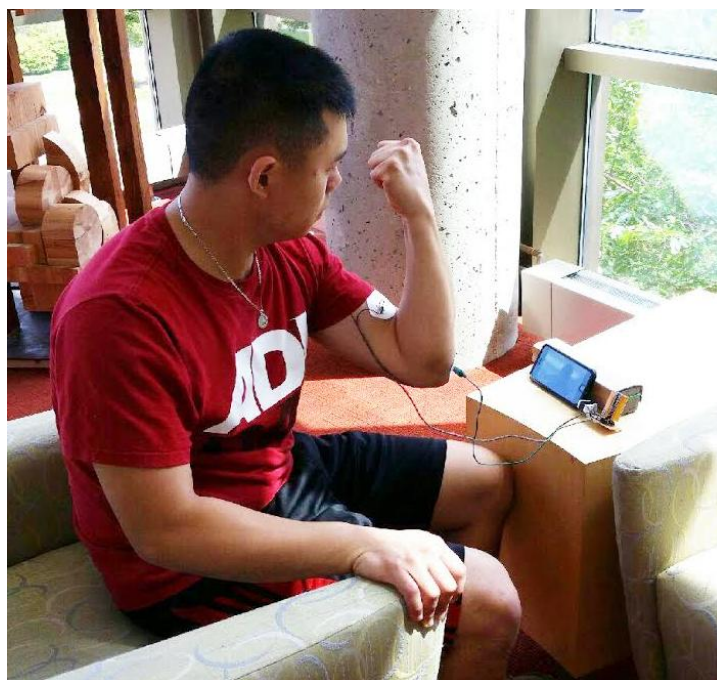
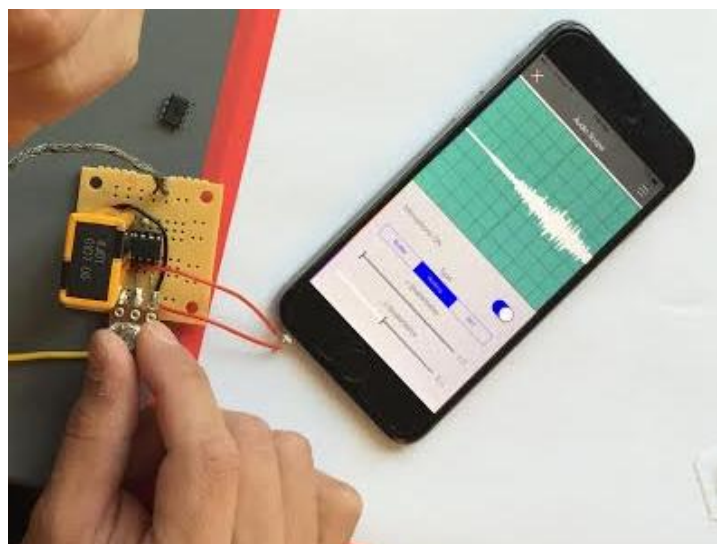
CONCLUSIONS

In this paper, we have described a laboratory activity in which students build and use their own minimalist electromyography. By engaging the students in constructing simple circuits that enable them to digitalize EMG recordings, we hope such exercises demystify the sophisticated and expensive equipment they will later use as they continue to develop their skills in electrophysiology. In doing so, we hope to permit the students to focus more on the data they are gathering and what the data means.

Because of the simplicity and low part count of the Breadboard amplifier, we feel that this technique has a great deal of potential to create interesting and impactful learning opportunities for students. Our data support our hypothesis that this device is relatively easy to build and use even by students with little electronics or physiology experience. Moreover, the compatibility with common, familiar media software leaves room for much experimentation and development, leading to sophisticated applications like video EMG and wireless EMG recordings.

Since its earliest days, neuroscience has been a field where sophisticated questions outpace current

Figure 7. The breadboard EMG method can be used in combination with streaming media platforms for remote data collection. *Top:* A student monitors his EMG using a soldered version of the amplifier connected to an iPhone. *Middle:* The student streams the recorded EMG (as the sound track) and corresponding video of the associated movement using Skype on an iPhone. *Bottom:* Another student watches the movement and monitors the EMG from a different location using Skype. He visualizes the EMG signals by using Audacity to acquire the auditory signal arriving over Skype. This can be done as simply as connecting an audio cable from the speaker jack to the microphone jack of the receiving computer (the “loop” method).



technologies and require the development of new innovations. We feel that introducing students to opportunities to build, use and modify instrumentation helps lay the groundwork for the next generation of innovators with flexible, interdisciplinary skills to answer tomorrow's neuroscience problems.

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APPENDIX A. Materials and tools required to construct the breadboard EMG amplifier circuit

- 1 x solderless breadboard
- 1 x Texas Instruments TLC252 dual operational amplifier
- 2 x 330 k Ω resistors
- 1 x 1 k Ω resistor
- 1 x 1 M Ω potentiometer
- 1 x 9 V battery
- 1 x 9 V battery connector
- 1 x 3.5 mm male phone plug (mono)
- 3 x alligator clips
- 1 x iMic or similar external sound card (optional)
- 3 x short jumper wires of varying length
- 3 x wire lengths (2-3' each)
- Soldering station (optional)
- Adhesive electrode pads

APPENDIX B. Post-exercise questionnaire.

Open Ended Questions

1. Have you ever taken a biology class? If yes, specify.
2. What worked well for you in the lab?

3. What problems did you experience in the lab? How frustrating were they? Did you solve these problems during lab? On your own? With the help from [your teaching assistant]? Not at all?
4. Were there areas where the instructor or [your teaching assistant] could have been of more help or better prepared? Please explain.
5. What was the best part of the lab? The worst part? Why?
6. Were you able to accomplish all of the tasks before the end of lab? If not, how far did you get, and what prevented you from finishing the entire exercise?
7. What suggestions do you have for improving the lab itself?
8. Would you recommend including this lab in future years? Why or why not? Be honest.
9. How could the lab manual be improved?
10. How useful were the readings (i.e., appendices) assigned before the lab? Were they too long?
11. Are there any parts of the manual that should be expanded upon? Which one(s) and why?
12. Are there any parts of the manual that were unclear or should be revised? Which one(s) and why?
13. Do you have any other suggestions that could help improve the lab itself or the lab manual?

Likert Scale Questions

Scale: -3 = disagree, 0 = neutral, +3 = agree (means \pm SEM)

1. I have prior experience with electronics and circuitry.
2. I have prior experience with electrophysiology equipment.
3. I was successful in acquiring EMG data in this experiment in 30 minutes.
4. I enjoyed doing this experiment.
5. I learned about electrical circuits in this experiment.
6. I understood what I was doing in this experiment.
7. The software to collect EMG data [Audacity] was easy to use.
8. The software I used was familiar.
9. The device [that I built] was easy to use.
10. I could use this device on my own again if I wanted to.

Received July 15, 2015; revised January 13, 2016; accepted January 15, 2016.

This work was supported by NSF IOS-1146243 to Drs. David Redish (University of Minnesota), Mark Masino (University of Minnesota) and Kevin Crisp (St. Olaf College), and by the St. Olaf College TRIO McNair Scholars Program. The authors thank Chris Stewart and Dr. Jeremy Loeback for technical assistance, execution, and feedback on this lab exercise, as well as for helpful feedback concerning the preparation of the manuscript.

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