Electromyography: Building an Amplifier Circuit

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Abstract

This project focuses on building, adapting and testing an amplifier circuit capable of capturing surface electromyography signals. The goal was to build a system that could detect the low voltage produced by muscle activity, condition the signal, and deliver a usable output for further analysis. The circuit uses an amplifier for the initial differential gain, followed by active filtering and a second gain stage to improve clarity and reduce noise. Surface electrodes were placed on the forearm to record muscle activation during simple contractions. The final circuit produced a stable and recognizable EMG waveform with a clear separation between the resting and active states.

1 Introduction

Electromyography is a method used to measure the electrical activity produced by muscle fibers when they contract. These signals carry important information about neuromuscular function, yet they are extremely small, typically ranging from a few microvolts to a few millivolts. Due to their low amplitude and susceptibility to environmental noise, raw EMG signals cannot be observed or analyzed without amplification and careful conditioning.

The purpose of this project is to build a multistage EMG amplifier circuit capable of detecting muscle activity from surface electrodes from scratch. The circuit comprises three main parts: an initial preamplifier stage that provides high input impedance and early gain, a differential amplifier stage that removes common electrical noise by comparing the two electrode inputs, and a dual power supply system that enables the operational amplifiers to process both the positive and negative portions of the muscle signal. Together, these elements form a complete signal chain that converts faint biological voltages into clear, measurable values.

2 Theoretical Background

2.1 Electromyography Signals

Surface EMG signals typically have amplitudes ranging from 0 to 10 millivolts [5]. The exact amplitude depends on various factors, including muscle size, electrode placement, skin impedance, and level of muscular contraction. Because these signals are differential in nature, each electrode pair detects voltage changes relative to a reference point on the body. EMG signals are vulnerable to many sources of interference. Common-mode noise from power lines, motion artifacts from electrode movement, and electrical activity from nearby electronics can all affect measurement quality. Skin impedance and physiological variability introduce additional distortions. These challenges make signal conditioning essential.

2.2 Operational Amplifier (OpAmp)

Operational amplifiers are high-gain electronic devices that are used to process small analog signals with precision. An op amp compares the voltages at its two input terminals and produces an output that is proportional to the difference between them. In an ideal model, the input impedance is infinite, the output impedance is zero, and the open-loop gain is extremely large. These properties make op amps suitable for amplification, filtering, buffering, and many types of analog computation.

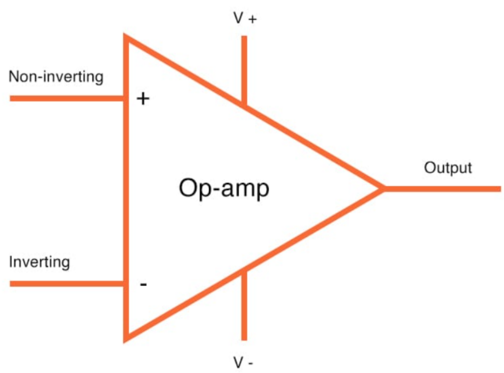

Figure 1: OpAmp in schematics [4]

In EMG circuits, the ability to amplify very small differential signals is essential. The amplifier must accept two inputs and respond only to their differences. High input impedance means that the amplifier draws almost no current from the electrodes. This prevents the circuit from loading the body and changing the voltage being measured, which helps preserve signal fidelity. Signal fidelity refers to the accuracy with which the measured signal represents the true physiological activity, without unwanted alterations, attenuation, or added noise. Low output impedance allows the amplifier to transfer its output to the next stage with minimal voltage drop. This ensures that the signal is delivered cleanly to filters or additional amplifiers without distortion or loss of amplitude.

The LF353 Operational Amplifier The LF353 is a dual operational JFET-input amplifier commonly used in biopotential amplification systems. Its JFET input stage provides extremely high input impedance (approximately $10^{12}\,\Omega$) and very low input bias currents (on the order of picoamperes), making it well suited for EMG, ECG, and EEG applications where electrode signals are weak and sensitive to loading. The device also offers low noise, low power consumption, and a relatively high slew rate, helping maintain clean and undistorted EMG waveforms throughout the signal chain. These characteristics are documented in the manufacturer's datasheet [1].

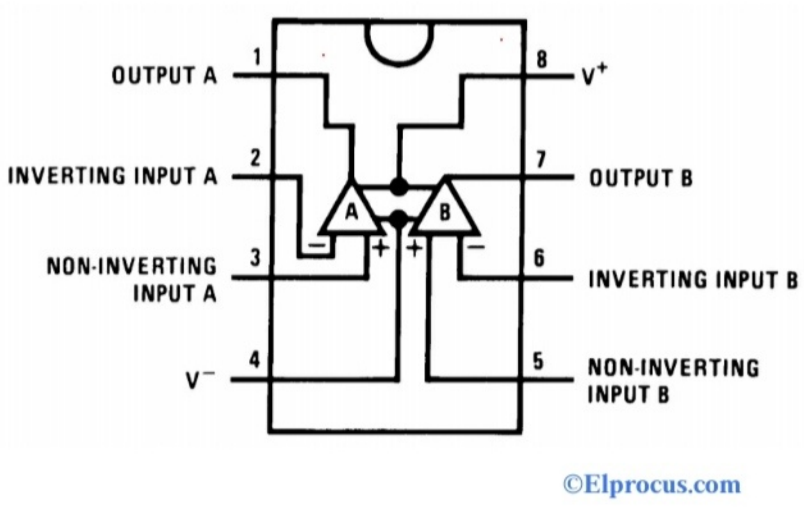

Figure 2: LF353 Pins [3]

3 Circuit Design and Components

3.1 Overview

The EMG amplifier is constructed in three main stages. The electrodes collect microvolt level signals which enter the preamplifier stage. The preamplifier provides high input impedance and modest gain. Its outputs feed the differential amplifier, which isolates true muscle activity by amplifying the voltage difference between electrodes. The power supply provides a stable ±15 volt rail required for the LF353 op amps. Each stage contributes to improving the overall signal to noise ratio.

3.2 Electrodes

The circuit uses three surface electrodes. Two measure electrical activity from the muscle, while the third serves as a reference. Because the signal is extremely small, the electrodes must be paired with a high impedance input. Good skin preparation and stable placement reduce motion artifacts and external interference.

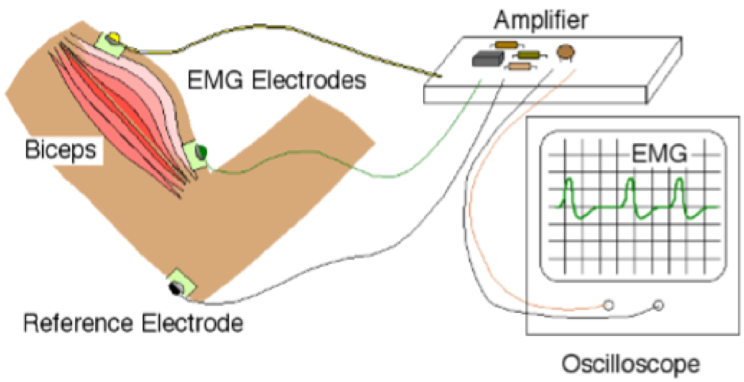

Figure 3: EMG Circuit System [2]

3.3 Preamplifier Stage

Each electrode channel is first connected to an LF353 operational amplifier configured as a voltage follower (unity-gain buffer). In this configuration, the output is directly fed back to the inverting input, while the electrode signal is applied to the non-inverting input. The negative feedback forces the amplifier to satisfy

$$V_{\mathrm{out}} = V_{\mathrm{in}}$$

which ensures that the preamplifier preserves the exact voltage present at the electrode.

Although this stage does not provide voltage gain, it performs essential conditioning functions for the EMG signal. The voltage follower provides extremely high input impedance, meaning that almost no current is drawn from the electrodes, preventing loading and maintaining the integrity of the microvolt-level signal. It also presents very low output impedance, allowing the signal to drive the subsequent differential amplifier stage without distortion and with sufficient current.

Generally, the preamplifier stage serves as an isolation buffer. Maintains the original EMG voltage waveform while converting it from a weak, high-impedance source to a stable, low-impedance signal suitable for precise amplification in the next stage of the circuit.

3.4 Differential Amplifier Stage

The buffered electrode signals feed a differential amplifier constructed from a single op amp and four resistors. This configuration rejects common-mode noise and amplifies the voltage difference corresponding to muscle activity. The electrode signals can be expressed in terms of differential-mode and common-mode components:

$$V_{\mathrm{dm}} = v_2 - v_1, \qquad V_{\mathrm{cm}} = \frac{v_1 + v_2}{2}.$$

For proper common-mode rejection, the resistor ratios must satisfy

$$\frac{R_2}{R_1} = \frac{R_4}{R_3}.$$

When this condition is met, the differential amplifier output becomes

$$v_3 = \frac{R_2}{R_1}(v_2 - v_1) = \frac{R_2}{R_1} V_{\mathrm{dm}}.$$

In this design, the resistors are chosen as

$$R_1 = R_3 = 680\ \Omega, \qquad R_2 = R_4 = 680\ \mathrm{k}\Omega,$$

which gives a differential gain of

$$A_d = \frac{R_2}{R_1} \approx 1000.$$

A capacitor at the output removes low-frequency drift through a high-pass filter formed with the input resistance of the oscilloscope. This ensures that slow baseline shifts do not obscure the higher-frequency EMG signals.

3.5 Power Supply

A dual ±15 volt power supply powers the preamplifier and differential amplifier. The LF353 is designed for dual supply operation. The three main nodes are:

- +15 volts to op amp pin 8
- −15 volts to pin 4
- 0 volts to ground

This provides enough headroom for the amplified EMG signal to swing above and below zero. This creates a total of thirty volts across the op amp, centered at ground. That margin is important because it prevents saturation during stronger muscle activity, provides sufficient room for high gain values, and allows the circuit to handle both the positive and negative parts of the EMG waveform without clipping.

3.6 Connection to the Oscilloscope

The output of the differential amplifier is connected to an oscilloscope via a 0.1 μF coupling capacitor. This capacitor blocks any DC offset while allowing the AC component of the EMG signal to pass. The oscilloscope ground connects to circuit ground, ensuring that the scope sees a zero-centered EMG waveform and only the changing muscle activity reaches the display.

4 Experimental Methods

4.1 Circuit Assembly

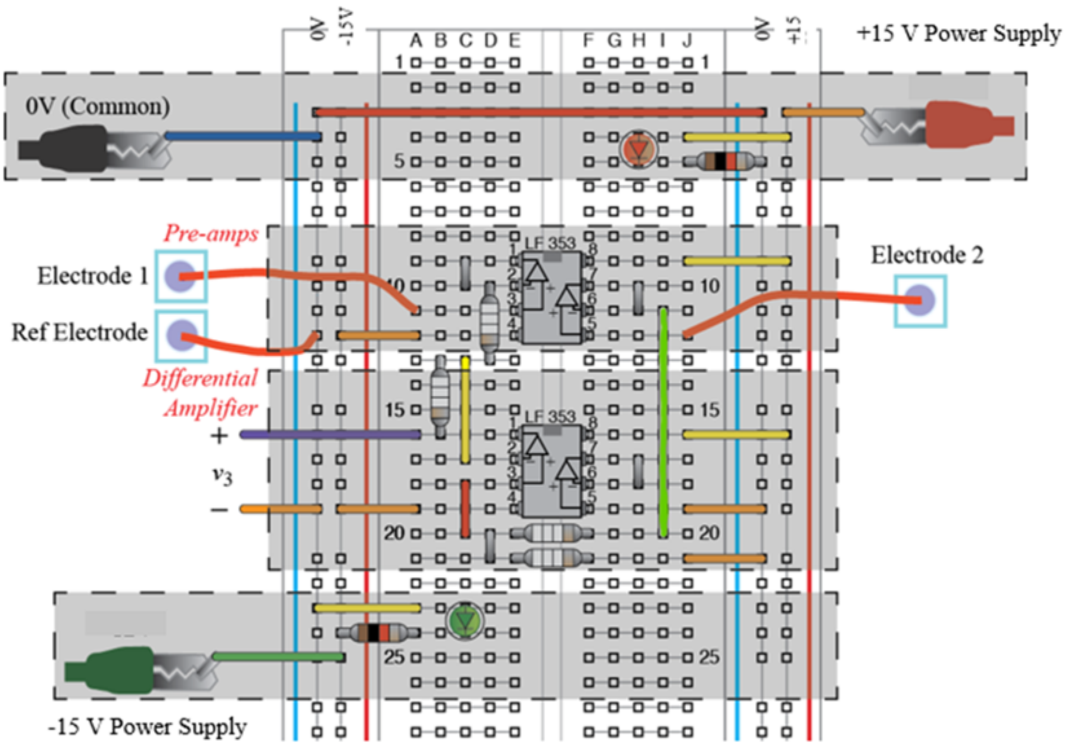

Figure 4: EMG Circuit [2]

4.2 Procedure

Step A: LED Power Indicator Test

The power supply connections to the breadboard were verified, with the +15V rail, -15V rail, and ground properly connected. Two LEDs, green and red, were used to test the rails: the green LED with a resistor was connected to the +15V line, and the red LED with a resistor to the -15V line. When power was applied, both LEDs illuminated, confirming that the positive and negative rails were active and stable.

Step B: Circuit Test with Signal Generator

Two signals from a signal generator were applied to the circuit: a 0.01 V sine wave and a 0.02 V sine wave. These inputs were used to verify the circuit's operation. The differential amplifier successfully amplified the voltage with a gain of 1000, producing an output of approximately 10.8 V on the oscilloscope. This closely matches the expected value, as the 0.01 V difference between the input signals multiplied by the gain of 1000 yields around 10 V. Additionally, when both input signals were set to 0.01 V, the oscilloscope displayed approximately 0 V, which is correct since the circuit amplifies the difference between the inputs. These results confirmed that the circuit was functioning as designed.

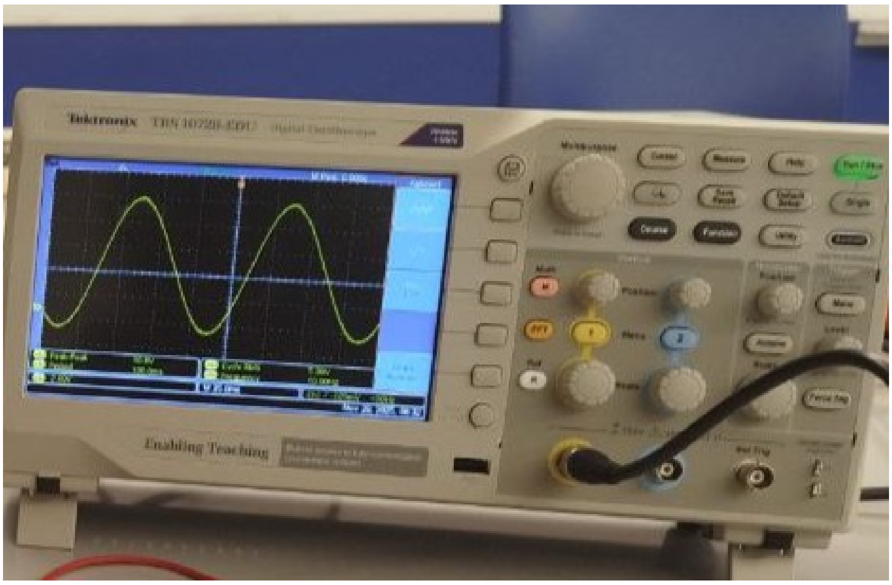

Figure 5: Oscilloscope setup showing the differential amplifier output. Inputs of 0.01 V and 0.02 V from the Signal Generator, and the amplified difference of approximately 10.8 V is displayed

Step D: Full Circuit Test with Electrode

After verifying the circuit with the signal generator, the input signals were replaced with signals from electrodes placed on the muscle. This allowed the full EMG circuit to be tested under real conditions. The differential amplifier successfully processed the signals from the electrodes, and the oscilloscope displayed the amplified muscle activity.

5 Results

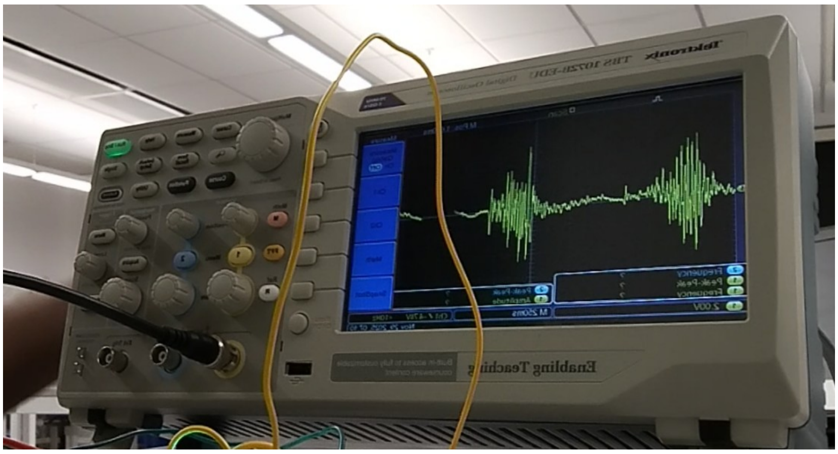

Figure 6: Oscilloscope display showing EMG signals from the bicep muscle. The waveform represents the amplified electrical activity detected by the electrodes, with distinct bursts corresponding to muscle contractions.

6 Discussions

Electromyography has a wide range of practical applications in both research and industry. EMG signals are used in medical diagnostics to assess neuromuscular disorders, in rehabilitation to monitor muscle recovery, and in prosthetics to control robotic limbs through muscle activation patterns. In sports science, EMG helps optimize training regimens and prevent injuries by analyzing muscle fatigue and recruitment. Additionally, EMG signals are increasingly used in human-computer interaction and wearable technology for gesture recognition, biofeedback systems, and exoskeleton control. These applications highlight the importance of designing accurate and reliable EMG acquisition circuits [5].

Looking forward, several experiments could further extend the functionality and understanding of this EMG circuit. One such experiment involves recording EMG signals while the subject lifts objects of varying weights, which could reveal how muscle activation amplitude and frequency components change with load (see Appendix for more details). Additionally, testing the amplifier on different muscle groups could highlight variations in signal characteristics due to muscle size and fiber orientation. Integrating digital data acquisition and real-time signal processing could enable analysis of contraction patterns, gesture recognition, or fatigue monitoring. Finally, exploring alternative electrode configurations could optimize the circuit for long-term monitoring.

7 Conclusion

The project successfully built and tested an EMG amplifier capable of detecting and amplifying surface muscle signals. The multistage design, incorporating a preamplifier, differential amplifier, and proper power supply configuration, provided high input impedance, accurate differential gain, and effective noise rejection. The circuit demonstrated reliable performance both with controlled signal generator inputs and actual electrode measurements from the bicep. This work highlights the feasibility of constructing low-cost, EMG circuit and provides a foundation for further applications in biomedical signal acquisition and analysis.

Acknowledgments

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References

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Appendix

Analysis of EMG Signals with Different Weights

In this experiment, EMG signals were recorded while lifting different weights to observe how muscle activation changes with load. Due to time constraints, the data collection method was relatively quick and not ideal. The peak-to-peak amplitude of the EMG signal was estimated visually by observing how high the signal jumped on the grid of the oscilloscope and approximating the corresponding voltage. Ideally, the EMG electrodes would be connected to a computer, and multiple trials would be recorded to calculate averages, standard deviations, and standard error of the mean for more accurate analysis.

Another limitation was the difficulty of electrode placement while performing the measurements on myself. Ideally, this procedure is better performed by two people: one to apply and monitor the electrodes and another to perform the muscle contractions.

Despite these limitations, measurements were taken for four weights: 0.5 kg, 1 kg, 2 kg, and 5 kg. The estimated peak-to-peak voltages were approximately 1 V, 2 V, 4 V, and 5 V, respectively. These results are consistent with expectations: as heavier weights are lifted, more muscle fibers are recruited, and the EMG signal amplitude increases. However, the rate of increase diminishes as most muscle fibers are already engaged as the weight increases, which explains why the change in voltage becomes less dramatic with larger weights.

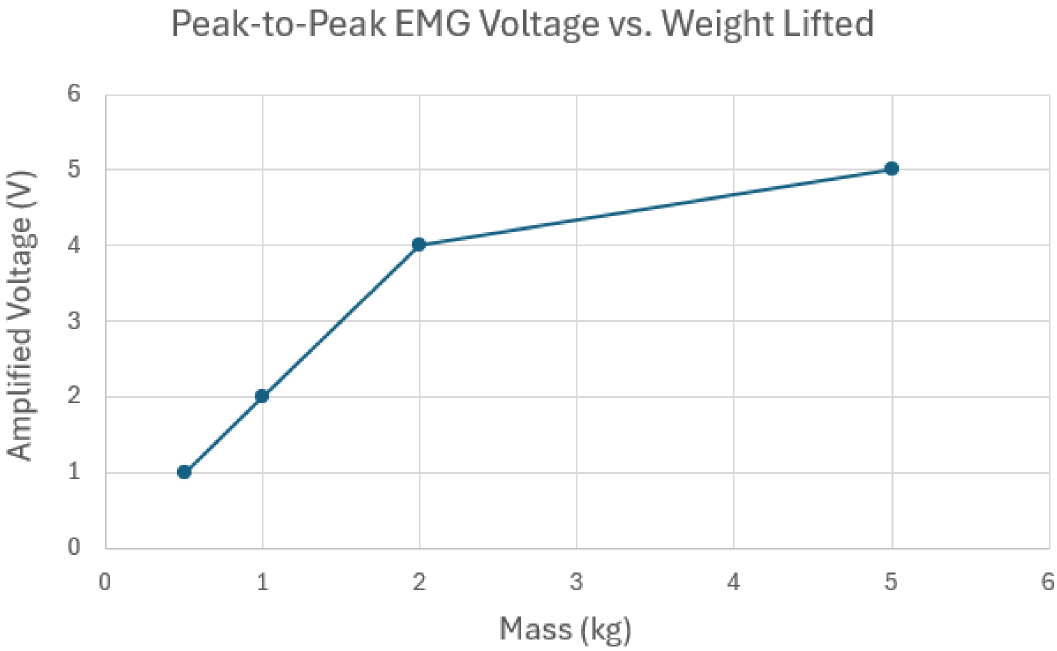

Figure 7: Peak-to-peak EMG voltage measured for different weights.

It is important to note that the absolute voltage output depends on many factors, including electrode placement and effectiveness, skin contact quality, and individual physiology. Therefore, the voltage measurements cannot be directly converted into a quantitative measure of muscle signal. Nevertheless, the trend of increasing EMG voltage with increasing weight provides useful qualitative insight into muscle activation.

Setup Pictures

The figures below show the experimental setup for the EMG measurements.

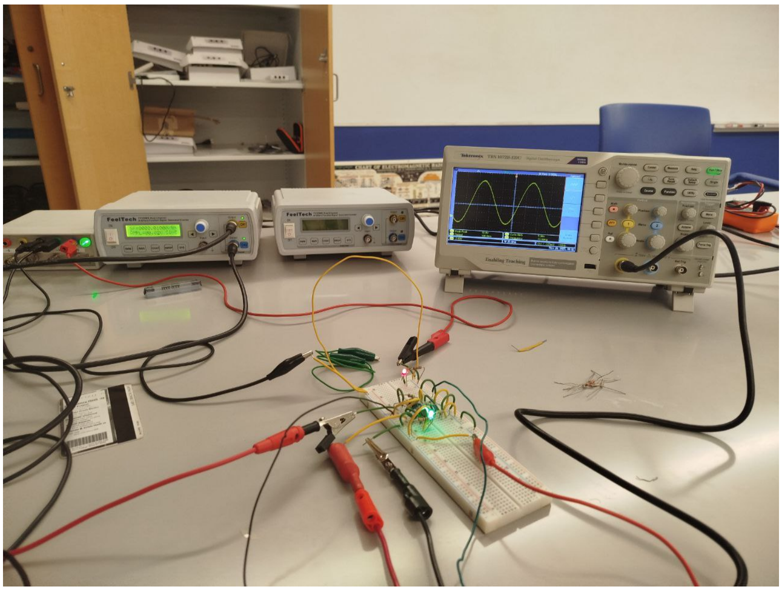

Figure 8: Testing the amplifier circuit with a signal generator.

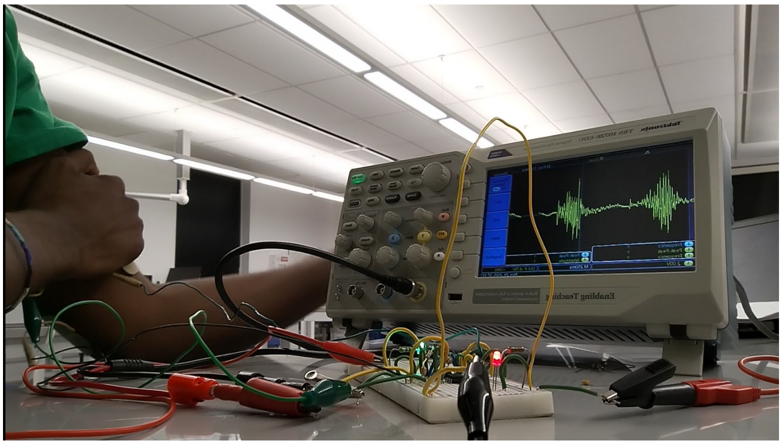

Figure 9: Electrodes placed on the biceps for EMG recording.