Laboratory Project 1:
Design of a Myogram Circuit

***Abstract*-You will design and build a circuit to measure the small voltages generated by your biceps muscle. Using your circuit and an oscilloscope, you will record plots of these voltages versus time. These plots are called electromyograms.**

I. Preparation

For the first laboratory project, which will last about four weeks, you will need the parts listed in Table I. You may purchase these parts from the stockroom next to the lab or purchase them elsewhere.

TABLE I
PARTS LIST

Item	Qnty	Description
1	1	Protoboard
2	1	Wire Kit
3	2	10 kΩ Resistors
4	2	20 kΩ Resistors
5	1	30 kΩ Resistor
6	2	LF353 Operational Amplifier
7	2	9 V Batteries (checked out from stockroom)
8	1	Package of Electrodes
9	4	Resistors (values you will compute)

II. Introduction

The gross muscle groups (e.g., biceps) in the human body are composed of a large number of parallel fiber bundles functionally arranged into individual motor units. When each motor unit is activated by nerve commands (action potentials) from the central nervous system, electrical impulses propagate down the length of the fibers that make up the unit. The electrical impulses can be picked up by electrodes and converted to voltages. A plot of the voltages from the muscles is called an *electromyogram*, or EMG ("myo" is a root meaning "muscle"). Fig. 1 shows the system for measuring an EMG.

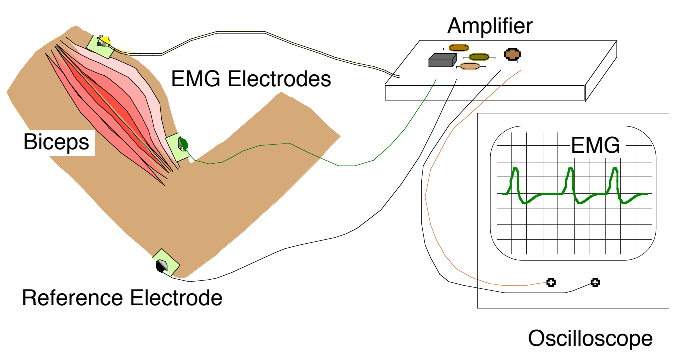


Figure 1. System for measuring an electromyogram.

EMG studies are useful for assessing the health of the neuromuscular system, since certain diseases, such as multiple sclerosis, slow down or even suppress normal nerve and muscle firing. In addition, several research groups have recently studied the possibility of using EMG signals to control artificial limbs for patients who have lost an extremity; the EMG signal would be obtained from a surviving portion of the limb and would represent the patient's central nervous system's desire to move the limb in a certain direction with a certain force.

III. Design Project

You will design and build an EMG circuit using two neighboring electrodes, placed on the biceps of the upper arm, to pick up the tiny electrical impulses generated by your nerves and muscle. A differential amplifier (studied in Section IX) is useful for amplifying the voltage drop between the signals from the two electrodes and for removing noise from external sources. A challenge arises, however, because the power in the signals on the electrodes is minute. Attaching the electrodes directly to a differential amplifier would draw a small current from each electrode, causing the voltage to drop to almost zero. We use pre-amps, studied in Sections IV-VIII, to solve this dilemma. The pre-amps can output higher current at the same voltage as the electrodes while drawing virtually zero current. Fig. 2 shows a block diagram of the electromyogram circuit with the pre-amps and differential amplifier that you will build in this lab. You will connect the output voltage, v_3, to an oscilloscope.

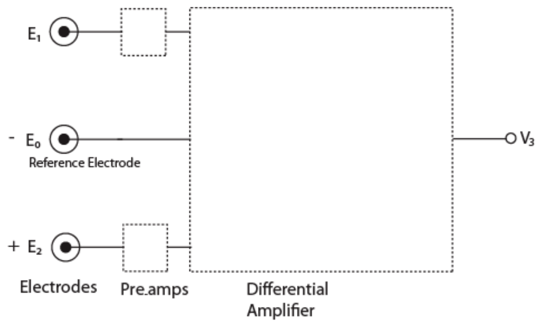


Figure 2. Block diagram of an electromyogram circuit.

IV. Measurements of Op-Amp Circuits for Pre-Amps

A. Modeling the Op-Amp as a Voltage Source

The purpose of this portion of the laboratory exercise is to investigate the behavior of basic op-amp circuits and find a circuit suitable for a pre-amp circuit to buffer the signals from the biceps. You will analyze two commonly used op-amp circuits: a negative-gain amplifier and a positive-gain amplifier. Afterwards, you will decide which circuit is best for sensing the weak EMG signals from the electrodes without loading them down, (i.e., without drawing current from them).

To reduce complexity, we model the op-amp as a power supply, (adjusted by hand). This reduces our circuits to a few resistors and voltage sources. Fig. 3 shows the two op-amp circuits that you will study. Fig. 4 shows how these circuits can be modeled using only resistors and an adjustable voltage source (or power supply). Note that the arrow on v_o indicates that v_o is an adjustable voltage source.

(a) (b)

Figure 3. Simple op-amp circuits: (a) negative-gain circuit, (b) positive-gain circuit.

(a) (b)

Figure 4. Circuits for modeling op-amp circuits: (a) negative-gain op-amp circuit, (b) positive-gain op-amp circuit.

B. Explanation of Op-Amp

Later in this section we will be compiling symbolic equations for our two commonly used op-amps circuits. These equations will then enable us to create a table of nominal values to compare with measured values from the circuits in Fig 4. This section describes the op-amp, and explains why we may replace it with an adjustable voltage source in our test circuits.

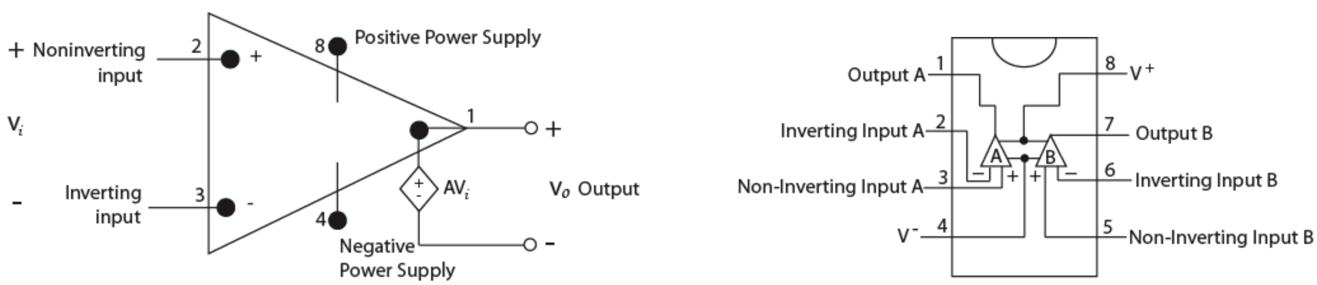
Fig. 5(a) shows a symbolic representation of an op-amp. The output of the op-amp acts like a dependent voltage source whose output voltage depends on the voltage drop across its input terminals. This means that $v_o = Av_i$ where v_i is the difference between the voltages at the + and – terminals, and A is some multiplication factor that we call the "gain" of the op-amp.

Inside an op-amp IC, there are many transistors and other components that you will study in detail in future courses. The net effect of this circuitry is to create an output voltage that is 10^5 or more times the size of the voltage drop across the + and – input terminals.

Using a negative feedback circuit that connects v_o back to the – input makes the input of your op-amp, v_i, become very small. Although we could use a complete op-amp model in our circuit, it is easier to assume that our negative feedback circuit is so effective that $v_i = 0$ and v_o has whatever value is necessary to make $v_i = 0$. This logic also justifies our use of an adjustable voltage source (i.e., power supply) in place of the op-amp. Like the power supply, the op-amp can output significant current. Since v_o may be larger than the input signal, (even with negative feedback), we find that our op-amp is able to amplify signals while increasing their current drive capability.

The LF353 op-amp we will use in this experiment is packaged as an integrated circuit (IC) in an 8-pin package and is shown in Fig. 5(b). The power-supply connections are the source of power the op-amp uses to create v_o, and we may think of the op-amp as routing either the positive or negative power-supply to the output, v_o. It is important to use the correct pins when wiring power to the op-amp, as incorrect wiring may cause the op-amp to be damaged.

As shown in Fig. 5(b), there are two op-amps in the LF353. To indicate which end is which, the IC package is shown with a small notch at the top. This notch is also on the actual plastic package and shows you which is the top end of the chip. The pins are numbered counterclockwise starting from the upper left, (looking down on the top of the chip). Note that this convention is the same for all chips. Figure 5(b) shows which pins are the power, ground, input, and output for the op-amp. Figure 5(a) only shows the model for one of these two op-amps. You will use the second op-amp in the chip to build a second pre-amp later on.



(a) (b)

Figure 5. LF353 operational amplifier: (a) Model, (b) Pins on package.

C. Measured Values of Resistors

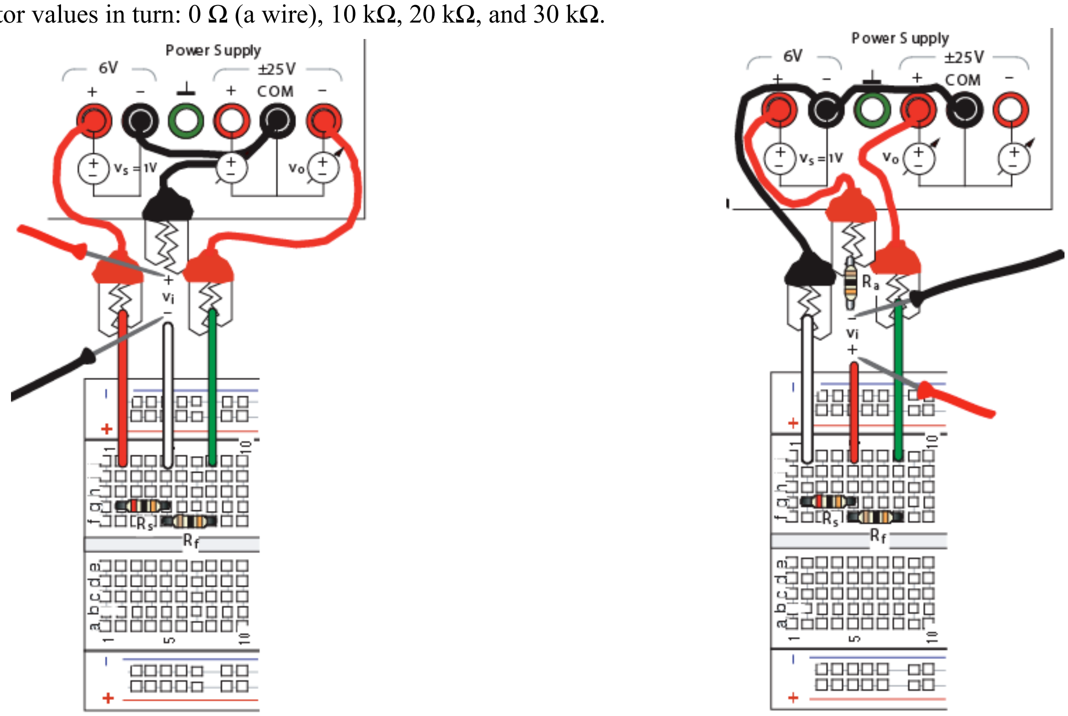
Before you begin working with your op-amp models, measure the actual values of your resistors. Using a digital multimeter set to the Ω setting, measure the values of the resistors by putting one of the meter's probes on one wire coming out of the resistor and one probe on the other wire coming out of the resistor. (If the probes are reversed, the measured value will be the same.) Fill out Table II (in your lab notebook) with the nominal and measured values for each of your resistors. The actual values for resistors will be used later on to improve the accuracy of calculations.

TABLE II
MEASURED RESISTANCES

Nominal Value	Measured Value
10 kΩ (a)	
10 kΩ (b)	
20 kΩ (a)	
20 kΩ (b)	
30 kΩ (b)	

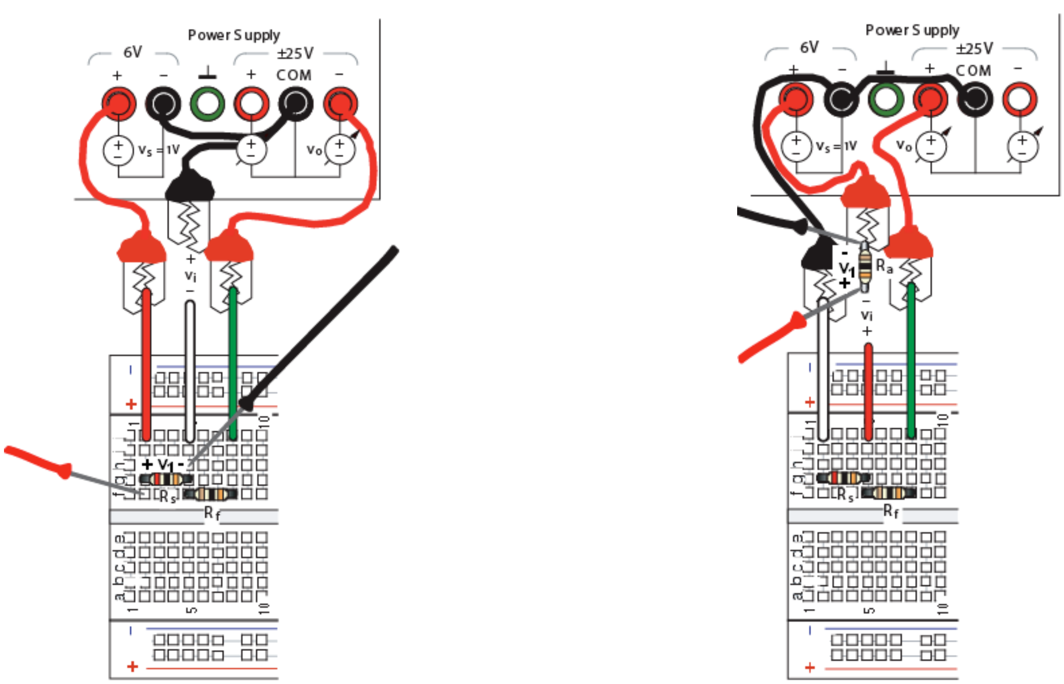
D. Measured Values of Voltages

Now we can construct the circuit in Fig. 4 on a protoboard, as shown in Fig. 6. Use the resistors you measured in the previous section and the power supplies at your lab bench for the voltage sources. Fig. 6 shows how to connect the power supply, which behaves like a set of batteries with adjustable voltages. Note how the voltage sources are connected inside the power supply. The controls on the power supply allow you to precisely adjust the source voltages. Your resistor value for R_s in both the negative-gain and positive-gain circuits should be 20 kΩ. For R_a in the negative-gain circuit, use a 10 kΩ resistor. For R_f, use each of the following resistor values in turn: 0 Ω (a wire), 10 kΩ, 20 kΩ, and 30 kΩ.



(a) (b)

Figure 6. Protoboard layouts for modeling op-amp circuits and measuring v_i: (a) negative-gain op-amp circuit, (b) positive-gain op-amp circuit.



(a) (b)

Figure 7. Circuits for modeling op-amp circuits and measuring v_1: (a) Negative-gain op-amp circuit, (b) Positive-gain op-amp circuit.

For v_s, use the power supply controls to set the output of the 6V supply to +1.00 V. Use the multimeter on the lab bench to measure v_i as shown by the red and black probes in Fig. 6. To measure voltage using the multimeter, set the multimeter dial to VDC. You will need a negative voltage for v_o for the circuit in (a). For each value of R_f, adjust the output of the +/-25V supply representing v_o until $v_i = 0$. In Table III, record the value of v_o from the power supply display and record the measured value of v_i from the multimeter display, (which should be very close to zero). Also, record the value of the voltage drop, v_1, across R_s or R_a as appropriate, (as seen by the pins in Fig. 7), being careful to use the proper polarity as shown in Fig. 7. (The values of v_1 will be used later to find the input resistance of the circuits.) Repeat the entire experiment for both circuits. You will need a positive voltage for v_o for the circuit in (b). Figs. 6 and 7 show the necessary power-supply connections.

Fill out Tables III and IV, below, with your measured values. (Be sure to include notes and circuit diagrams in your lab book. It may be useful to cut and paste this lab write-up into your lab book as well.) Note that, in this section, you will only fill out measured values. You will find the expected values later on and may check back to see whether your values are consistent with the expected values. Values in parentheses in Tables III and IV give some idea of the expected values.

TABLE III
NOMINAL AND MEASURED VALUES FOR NEGATIVE-GAIN OP-AMP CIRCUIT

R_f (nominal)	R_s (nominal)	v_i (≈ 0 V)	v_o (> –3 V)	v_1 (< 2 V)
0 Ω	20 kΩ			
10 kΩ	20 kΩ			
20 kΩ	20 kΩ			
30 kΩ	20 kΩ			

TABLE IV
NOMINAL AND MEASURED VALUES FOR POSITIVE-GAIN OP-AMP CIRCUIT

R_f (nominal)	R_s (nominal)	v_i (≈ 0 V)	v_o (< 3 V)	v_1 (≈ 0 V)
0 Ω	20 kΩ			
10 kΩ	20 kΩ			
20 kΩ	20 kΩ			
30 kΩ	20 kΩ			

V. SOLUTIONS OF OP-AMP CIRCUITS FOR PRE-AMPS

A. Using Kirchhoff's Laws to Find an Expression for v_o and v_1

Referring back to Fig. 3, you will now find symbolic expressions for v_o and v_1 for your negative and positive gain amplifiers. To simplify this process we can reduce our op-amp circuits to a model of the op-amp circuit as shown in Fig. 4. Almost no current flows into the + and – inputs of the op-amp—as though the op-amp were absent. Consequently, as discussed earlier, in a circuit with negative feedback we may analyze the behavior of the op-amp by removing it from the circuit entirely and replacing it with a voltage source, v_o, that is adjusted until the voltage drop across the + and – inputs equals zero. We employ this method of analysis because the simplified circuit is simple enough that we may solve it using a few equations resulting from Kirchhoff's laws. Later on, we will assume the op–amp is present again and producing the output voltage, v_o.

Using Kirchhoff's laws and Ohm's law, analyze each op-amp circuit in Fig. 4 and derive an expression for v_o and v_1. The expression must not contain more than the circuit parameters R_f, R_s, and v_s. (Hint: First, solve for v_o versus v_s by assuming $v_i = 0$ V, and using voltage loops that include v_i.) You will use your equations for v_o and v_1 to derive a table of expected values in the next section.

B. Expected Voltages

Using the equations for v_o and v_1 that you derived above, fill out the Tables IV and V with your expected values. Make sure to use your measured values for resistors when calculating your expected values, and use v_s = 1.00 V or the value you measured for v_s. Comment on how your measured values compare your expected values, calculate the maximum error in percent.

TABLE V
EXPECTED VALUES FOR NEGATIVE-GAIN OP-AMP CIRCUIT

R_f (nominal)	R_f (measured)	R_s (nominal)	R_s (measured)	v_i (≈ 0 V)	v_o (< 3 V)	v_1 (≈ 0 V)
0 Ω		20 kΩ				
10 kΩ		20 kΩ				
20 kΩ		20 kΩ				
30 kΩ		20 kΩ				

TABLE VI
EXPECTED VALUES FOR POSITIVE-GAIN OP-AMP CIRCUIT

R_f (nominal)	R_f (measured)	R_s (nominal)	R_s (measured)	v_i (≈ 0 V)	v_o (< 3 V)	v_1 (≈ 0 V)
0 Ω		20 kΩ				
10 kΩ		20 kΩ				
20 kΩ		20 kΩ				
30 kΩ		20 kΩ				

VI. LINEAR AMPLIFIER RESPONSE

A. *Linearity*

To produce an accurate measurement of voltages from biceps, we require amplifiers that produce output voltages that are linear with respect to their input voltages. Linearity means the function relating output voltage to input voltage is a straight line. In this section you will assume linearity to characterize your amplifier.

B. *Plot of v_o versus v_i*

Plot *by hand* the values of $x = R_f/R_s$ versus $y = v_o/v_s$ for both the positive and negative-gain op-amp circuits. That is, calculate the value of v_o/v_s and R_f/R_s for each measurement. Make a table of these values in your lab notebook. Use your measured values for resistors for an accurate fit. Then plot your values as the x and y coordinates on a piece of graph paper placed in your laboratory notebook. After plotting the data points, use a ruler to draw a straight line that is the best fit to the four data points on each plot. You will have two plots: one for the negative-gain amplifier and another for the positive-gain amplifier.

C. *Line Equation for v_o versus v_i from Plot*

Write down equations for your straight line fits for the plots of $y = v_o/v_s$ versus $x = R_f/R_s$ for each op-amp circuit. That is, determine, (with additional ruler measurements on your plot), the values of a and b in the equation for each straight line that you drew above:

$$y = ax + b \tag{1}$$

D. *Linear Expression for v_o versus v_i using Polyfit*

Using your measured data and the polyfit function in Matlab®, find a linear, (i.e., polynomial of order one), equation for $y = v_o/v_s$ versus $x = R_f/R_s$ for each op-amp circuit. Use your measured values of resistors for an accurate polyfit. See code from polyfit_diode.m in the Pseudo-Laboratory Project handout for an example of how to perform this task, or type "help polyfit" in Matlab®. This process will give you values of a and b for a least squares fit of your data. This should be slightly more accurate than your estimate based on using a ruler.

E. *Symbolic Expression for v_o versus v_i*

Using equations for v_o (from the previous section) for both the positive-gain and negative-gain op-amp circuits, find the symbolic expressions for a and b for the straight-line equation for $x = R_f/R_s$ versus $y = v_o/v_s$. That is, rearrange your equation for v_o versus v_s so that you have v_o/v_s equal to some function of R_f/R_s. Using the symbolic expressions and resistor values, find the numerical values of a and b. Estimate the percent difference in the values for a and b from each of the three different methods of finding a straight-ling fit: plotting by hand, using polyfit in Matlab®, and using symbolic expressions and algebra. Comment in your notebook on how similar the results are for these three methods of finding a straight-line fit.

VII. PRE-AMP INPUT RESISTANCE

A. *Calculated Input Resistance*

The input resistance of a circuit is the resistance that, when placed directly across v_s, would draw the same current from v_s as the entire actual circuit. By Ohm's law, the input resistance is equal to v_s divided by the current, i_1, flowing out of the v_s source:

$$\mathrm{R}_{in} \equiv \frac{v_s}{i_1} \tag{2}$$

Circuits with high input resistance draw little current and appear like they do not exist to the circuit in front of their input. We would like our pre-amp input resistance to be high. It is somewhat inconvenient to measure current i_1 directly in our circuits, as the current meter must be inserted in the circuit so that the current from the v_s source flows through it. To avoid this inconvenience, we determine i_1 by measuring the voltage drop across a resistor in series with the v_s source, (which you did earlier), and using Ohm's law to find the current. Use this idea and Kirchhoff's laws to find a symbolic expression for the input resistance, R_{in}, as a function of resistors in each circuit. Fig. 8 gives visual representations for R_{in} for your negative and positive-gain circuits from Fig. 4.

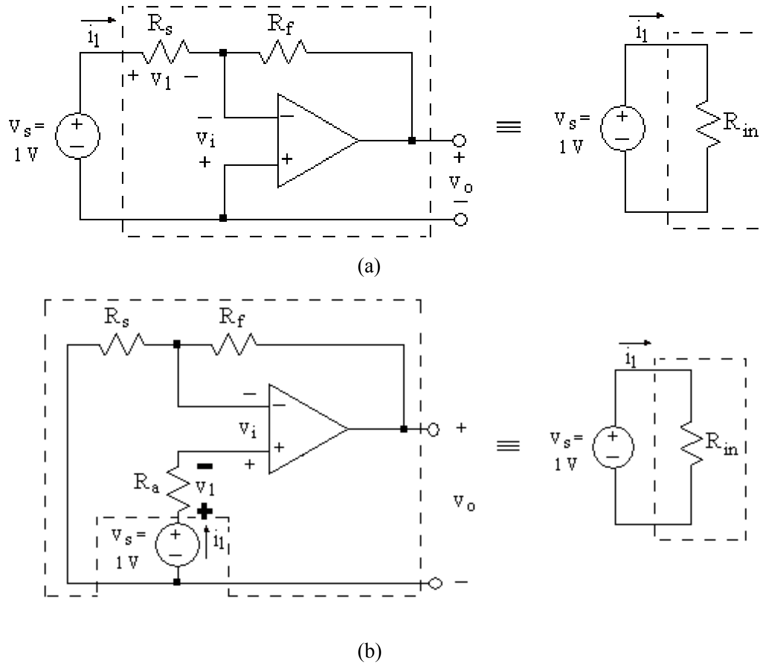


Figure 8. Input resistance Rin for pre-amp circuits: (a) negative-gain circuit (b) positive-gain circuit

B. Measured Input Resistance

Using (2), $v_s = +1.00$ V (or whatever actual value of v_s you used), and your measured values of i_1 from earlier, calculate the measured input resistance, R_{in}, for the negative and positive-gain amplifiers. Fill out Tables VII and VIII with the values of R_{in} calculated from your formula using measured resistor values and the values of v_s and i_1. (Extremely high values of input resistance are desirable for the pre-amps, as this means the electrode is effectively driving an open circuit, which requires zero power.)

TABLE VII

INPUT RESISTANCE CALCULATIONS FOR NEGATIVE-GAIN OP-AMP CIRCUIT

R_s	v_1	i_1	R_{in}

TABLE VIII

INPUT RESISTANCE CALCULATIONS FOR POSITIVE-GAIN OP-AMP CIRCUIT

R_a	v_1	i_1	R_{in}

VIII. Pre-Amp Design and Test

A. Design

Based on the above results and analysis, design a pre-amp for the electromyogram circuit. (The final circuit will have two identical pre-amps.) The design objectives for the pre-amp are twofold:

1) *Infinite input resistance:* $R_{in} = \infty\ \Omega$
2) *Unity gain:* $v_o/v_s = 1$

Choose which operational-amplifier circuit from above to use, given these requirements. Eliminate all unnecessary components. (Your final circuit will be very simple.) Note that the design objectives yield a circuit that draws no current from the electrodes, (because it has infinite input resistance), and outputs the electrode voltage, (because it has unity gain). A unity-gain amplifier is sometimes called a voltage flower because the output voltage follows the input voltage. Our op-amp circuit is thus a voltage follower. It is able to drive the differential amplifier that follows it without significant loss of signal.

B. Calculated Input Resistance

Build the two identical pre-amp circuits on your protoboard using one LF353 op-amp integrated circuit. (The LF353 contains two op-amps in an 8-pin dual-in-line package.) See Fig. 5(b) or http://www.national.com/ds/LF/LF353.pdf for the pin numbers of the op-amp.

The LF353 requires a +9V and a –9V power supply connection for this laboratory exercise. Fig. 9 shows how to connect the laboratory power supply. When taking actual EMG measurements, you will use two 9V batteries to supply power but, while testing the circuit before connecting to your arm, you may use a laboratory power supply. Be sure to connect the COM output, shown connected to a "rail" running down the side of the protoboard, to appropriate points in the circuit. How you lay out the remainder of the circuit on the protoboard is up to you. Test the pre-amps by inputting various voltages between –7 V and +7 V and measuring the output voltages. The input voltage and output voltage should differ by at most a few millivolts.

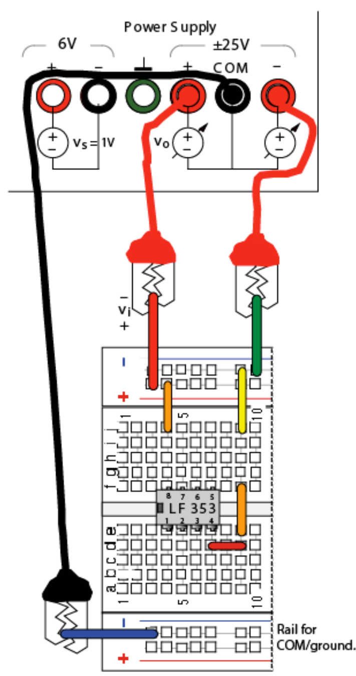


Figure 9. Protoboard and power-supply connections for power to op-amp.

IX. Differential Amplifier

A. Overview

Our electromyogram circuit uses two electrodes on the biceps and a reference (ground) electrode on the elbow. Each electrode on the biceps picks up a different voltage from the muscle, along with electrical noise that is present in all voltage measurements. The difference between these muscle voltages is the signal that we wish to amplify and record. A differential amplifier performs this task by amplifying only the difference between two voltages. Simultaneously, the differential amplifier helps to suppress noise signals, such those from the surroundings, that affect both electrodes the same way. The term "differential mode" refers to the difference between two voltages, v_{dm}, whereas the term "common mode" refers to the sum of two voltages, v_{cm}.

$$v_{cm} \equiv \frac{(v_2 + v_1)}{2} \tag{3}$$

$$v_{dm} \equiv v_2 - v_1 \tag{4}$$

Ideally, our differential amplifier's differential-mode gain will be large, while the common-mode gain will be small. Fig. 10 shows the differential amplifier we use for this laboratory project.

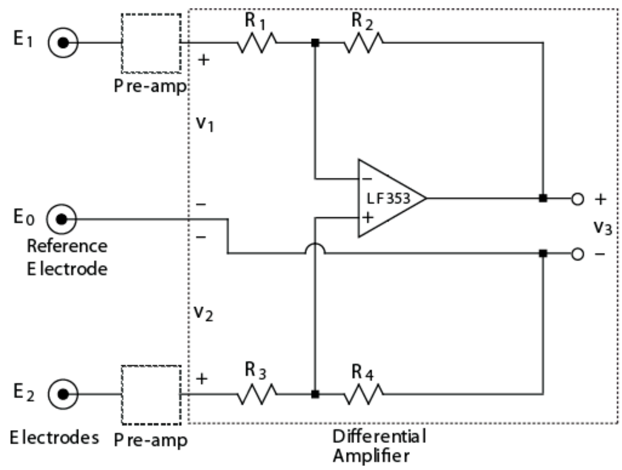


Figure 10. Schematic diagram of electromyogram circuit.

B. Expression for v_3

Using Kirchhoff's laws and Ohm's law, analyze the differential amplifier circuit shown in Fig. 10. Derive the expression for v_3 as a function of input voltages v_1 and v_2 and resistances R_1, R_2, R_3, and R_4. Be sure to incorporate the 0 V drop across the op-amp inputs, because it is operating in the linear mode, and replace the op-amp with a voltage source called v_o.

We want v_3 to be proportional to only the difference between v_1 and v_2. This is important so that any offset voltage common to both electrodes (v_{cm}) caused by a source other than nerve and muscle activity will be cancelled out. (Furthermore, electronic noise generated by non-ideal characteristics in our circuit will typically be the same for both electrodes and will be cancelled out.) To determine how to make the common-mode gain zero, rewrite the formula for v_3 in terms of the common-mode signal, v_{cm}, and the differential-mode signal, v_{dm}, defined in (3) and (4). Begin this process by making the following substitution:

$$v_1 = v_{cm} - \frac{v_{dm}}{2} \tag{5}$$

$$v_2 = v_{cm} + \frac{1}{2} v_{dm} \tag{6}$$

Show that v_3 is a function of only v_{cm} if the ratio of R_1 to R_2 is the same as the ratio of R_3 to R_4. To do so, first rewrite v_3 in terms of the following ratio, $\Re$:

$$\Re = \frac{R_1}{R_2} = \frac{R_3}{R_4} \tag{7}$$

Then show that v_{cm} disappears from the expression for v_3.

C. Design

Based on the above analysis, design a differential amplifier for the electromyogram circuit. There are four design objectives for the differential amplifier:

1) The differential gain of the circuit must be 500. The differential gain is the term multiplying v_{dm} in the equation for v_3. This makes the output as large as possible without causing the output to "saturate" by reaching the op-amp power supply voltages. (The output is limited by the power-supply voltages, resulting in clipping distortion of the output waveform if the voltage reaches the level of the power supply.)

2) The input resistance, (input voltage divided by input current), must be the same for both inputs. This will help cancel out less than ideal output characteristics of the pre-amps. The input resistance must be the same because we have a small signal and need the same load on both signals to avoid any distortion arising from asymmetry.

3) The input resistance for both inputs must be high enough that the input current never exceeds the maximum current, (10 mA), that the op-amp in the pre-amp can supply. Use worst-case op-amp output voltage $v_o = + v_{rail}$ to determine the minimum R_{in} allowed. Note that actual voltages out of our pre-amps will be small, and exact values are unknown.

4) The maximum resistor values used in your circuit (R_1, R_2, R_3, and R_4) should only slightly exceed 1 MΩ. This is because even a small noise current in our circuit can create a larger voltage across a high-valued resistor, so we limit the resistor size in order to limit the voltage this small noise-current will create across the resistors.

D. Testing

Build the differential amplifier circuit. Test your differential amplifier by using voltage dividers as shown in Fig. 11. Use the laboratory power supply for v_{s1} and v_{s2}.

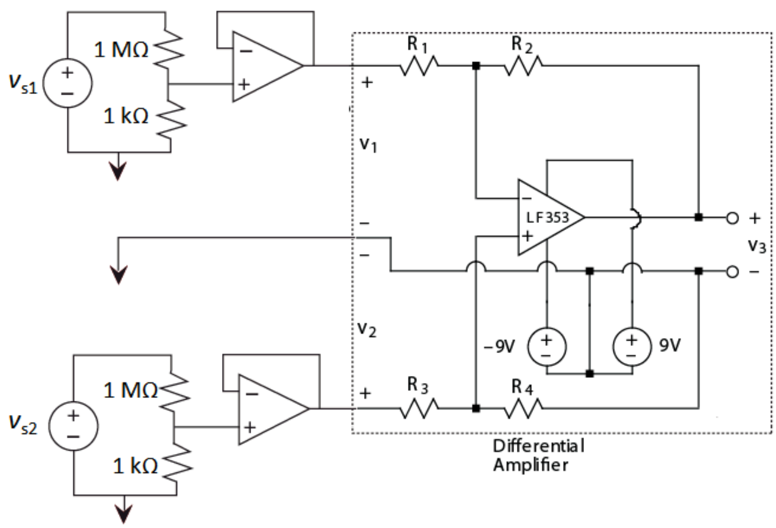


Figure 11. Testing differential amplifier using voltage dividers. (Arrow represents reference.)

Note that you will be using voltage-dividers to create small input voltages for the pre-amps. Measure the differential-amplifier output voltages for several different pairs of input voltages. Make a table of the results.

E. Measured Gain

Verify that the gain of the differential amplifier is close to 500. To calculate the gain, divide the *change* in output voltage between two sets of measurements, Δv_3, by the *change* in the difference input voltage for the two sets of measurements, $\Delta(v_2 - v_1)$.

$$\text{D}iff.\,Gain = \frac{\Delta v_3}{\Delta(v_2 - v_1)} \tag{8}$$

This method of calculating the gain eliminates a large constant offset in the output that results from an offset voltage across the + and – inputs. This offset voltage is only a few millivolts and represents the voltage across the + and – inputs that the op-amp interprets as exactly zero volts. In many applications this offset voltage may be neglected. In the differential amplifier circuit, however, the offset voltage is similar in size to the input signals and also gets multiplied by 500, causing a significant output voltage even when the two signals driving the differential amplifier are zero.

X. ELECTROMYOGRAM

A. Electromyogram Plot

Use two 9 V batteries as the power supplies for your electromyogram circuit.

Connect electrodes to your biceps—the muscle on the top of the upper arm that bulges when showing off your strength. Place two electrodes, measuring the voltages going into the preamps, about three inches apart, on the upper and lower end of the biceps slightly toward the outside of the muscle. Place the third, reference electrode, on the elbow. (Avoid placing the reference electrode on muscle.)

Connect the output of the electromyogram circuit to an oscilloscope. To eliminate the large constant vertical (DC) offset of the waveform, place a 0.1 μF capacitor between the differential amplifier output and the oscilloscope probe. That is, attach the oscilloscope probe to one side of the capacitor and connect the other side of the capacitor to the differential amplifier output. Observe the waveform on the oscilloscope and capture an example of the waveform that you can plot in Matlab® on a computer. (See instructions under Matlab® on course website.) Print out copies of the waveform for both the lab notebook and report.

B. Matlab® Code to Calculate Electromyogram Power

Write Matlab® code to calculate the average "power" of the recorded waveform by calculating the average value of voltage squared:

$$p = \frac{1}{N}\sum_{i=1}^{N} v_{3i}^2 \tag{9}$$

where

- p is the average "power" of the output signal
- N is the number of sample points
- v_{3i} is the ith sample of the output voltage

(Note that p actually has units of voltage squared rather than power, but p is equal to the power we would have if we connected a 1 Ω resistor to the output of the circuit.)

C. Plot of Electromyogram Power versus Weight

Measure the average circuit output power, p, while holding the lower arm horizontal with no weight, one unit of weight, two units of weight, and three units of weight. Choose weights such that the three-unit weight requires significant but comfortable effort when held with the lower arm horizontal. When performing the tests with weights, keep your joints in a constant position as much as possible.

Using Matlab®, make a plot of p versus weight. Comment on the shape of this plot.

XI. NOTEBOOK AND REPORT

Turn in a copy of your laboratory notebook pages and a separate formal report. Refer to the grading information on the course website for the section numbering to use while writing the formal report. Use the IEEE format for typesetting. Information about the IEEE format, including a template file, is available on the course website. Additional information about writing the report and keeping a notebook is listed in the *Course Procedure* on the course website. Note that Matlab® code and plots must appear both in the laboratory notebook *and* the formal report.

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