Measuring Forearm Behavior in Weight Lifting Using Strain Gauge and Surface Electromyography on the Triceps Muscle

Sensing & Measurements project

Sharif University of Technology

Department of Electrical Engineering

Supervisor: Dr. Mehran Jahed

Seyyed Amirmahdi Sadrzadeh | 401102015
Aisa Sadat Takyar | 401101462
Mohammadkazem Shahrabi | 401101987

February 6, 2025

Abstract

This report presents the design and development of a biomechanical recording system aimed at analyzing forearm movement during weightlifting activities. The system combines strain gauge sensors for force measurement at the gripping section of the weight and surface electromyography (sEMG) to capture muscle activity in the triceps brachii. By integrating these two sensing technologies, the system provides valuable data on muscle activation, force exertion, and movement dynamics. This project addresses key challenges in signal quality, including motion artifacts, noise from powerline interference, and the need for precise calibration. The results demonstrate the system's capability to provide accurate, real-time data that can be applied in various fields such as rehabilitation, sports science, and prosthetics development. Future improvements could focus on enhancing system portability and exploring advanced data analysis techniques for real-time muscle-force relationship evaluation.

Contents

1 Introduction

Understanding human motion and muscle activation patterns is crucial in biomechanics, rehabilitation, and sports science. One method to analyze these movements is through a recording system that integrates strain gauge sensors and surface electromyography (sEMG). This system allows for the quantitative measurement of forearm behavior when lifting and lowering a weight, providing insights into muscle activation, force exertion, and mechanical load distribution. In this project, a strain gauge is placed at the gripping section of the weight to measure force changes, while a two-electrode surface EMG is applied to the triceps brachii to record muscle activity. The combination of these techniques enables precise tracking of forearm mechanics and neuromuscular responses, which are essential for applications such as strength training, prosthetic control, and injury prevention.[9] [15] [24]

2 Literature Review

2.1 Existing Systems and Their Specifications

Several advanced systems are currently used for EMG-based muscle activity analysis and strain gauge-based force measurement. Below are some of the most notable ones:

1. Delsys Trigno EMG System [8]
   - **Features:** Wireless, high-precision EMG with built-in accelerometers.
   - **Application:** Used in clinical research, sports science, and prosthetic development.
   - **Advantages:** High signal quality, minimal noise interference, real-time data processing.
2. Biometrics Ltd DataLOG EMG System [16]
   - **Features:** Portable, multi-channel sEMG system with force sensors.
   - **Application:** Used for real-time motion analysis and rehabilitation monitoring.
   - **Advantages:** High sampling rate, compact design, easy integration with force sensors.
3. Tekscan Grip System (for Strain Gauge Measurement) [18]
   - **Features:** Thin-film force sensors embedded in gloves for grip force analysis.
   - **Application:** Used in ergonomic studies, rehabilitation, and grip strength evaluation.
   - **Advantages:** High-resolution force measurement, flexible sensor placement.

2.2 Best System for our Application

For our specific project (measuring forearm movement with strain gauge and sEMG on the triceps brachii), the best system would be:

- Delsys Trigno Wireless EMG (for its high accuracy and ease of integration).
- Custom-built strain gauge system (for precise force measurement at the gripping section of the weight)

In this project, we will develop a biomechanical recording system to analyze forearm movement during weightlifting and lowering using the triceps brachii muscle. The system will integrate surface electromyography (sEMG) and a strain gauge to capture muscle activation and force exertion simultaneously.

2.3 Example Studies and Applications

- Biomechanics Research: Studies often use sEMG combined with force measurements to study muscle fatigue and force generation, such as in lifting tasks or sports applications.

  Recent Study: Fradkin, A. J., et al. (2020). "Application of surface electromyography for muscle fatigue analysis during dynamic movements." Journal of Sports Science & Medicine, 19(1), 35-45.
- Wearable Devices: Wearable muscle sensing systems are increasingly used in sports science for tracking muscle performance, in rehabilitation for muscle recovery, and in prosthetics for real-time muscle control.

3 Use and Application

3.1 Importance of the Recording System

1. Biomechanical Analysis: Capturing muscle activity and mechanical load simultaneously helps in understanding how the triceps brachii contributes to weight lifting and lowering movements.
2. Medical and Rehabilitation Applications: The system can assist in diagnosing muscle fatigue, optimizing rehabilitation exercises, and evaluating neuromuscular disorders.
3. Ergonomics and Sports Science: Studying muscle activation under different loads can aid in designing better training regimens and preventing overuse injuries. [26] [27]

3.2 Applications of the Recording System

The integration of surface electromyography (sEMG) and strain gauge sensors in biomechanical studies has broad applications, particularly in:

1. Rehabilitation & Medical Diagnosis
   - Monitoring muscle activation in patients recovering from injuries or neurological disorders.
   - Evaluating muscle fatigue and neuromuscular diseases like Parkinson's and ALS.
2. Sports Science & Strength Training
   - Optimizing athletic performance by analyzing muscle recruitment patterns.
   - Preventing overuse injuries by assessing muscle load under different resistance conditions.
3. Ergonomics & Prosthetics Development
   - Designing more effective prosthetic limbs by understanding natural muscle activation.
   - Improving workplace ergonomics to reduce repetitive strain injuries.

4 Challenges and Considerations in Existing Systems and Circuit/Signal Acquisition Design

4.1 Signal Quality Challenges

1. Noise and Artifacts in sEMG Signals [6]
   - Motion Artifacts: sEMG systems are highly sensitive to motion artifacts (e.g., movement of electrodes on the skin), which can lead to false readings of muscle activity during dynamic movements.
     Solution: Use longer electrode cables with shielding or wireless systems like Trigno™ Wireless EMG System that reduce electrode motion. Additionally, incorporating high-pass filters (e.g., cutoff at 10–20 Hz) can reduce baseline shifts caused by motion.
   - Powerline Interference: 50/60 Hz powerline interference is a common issue, especially in environments with many electrical devices.
     Solution: Notch filters (50/60 Hz) are used to eliminate this noise.
   - Cross-talk: When recording from multiple muscles, cross-talk (interference from adjacent muscles) can distort the readings.
     Solution: Placing electrodes in areas with a low risk of cross-talk and using differential electrodes with high Common Mode Rejection Ratio (CMRR) can reduce this problem.

2. Strain Gauge Signal Issues [25]

    - Small Signal Magnitude: The signal output from strain gauges, particularly in low-load conditions, is typically very small, often in the mV range, making it prone to noise and distortion.

      Solution: The use of high-precision instrumentation amplifiers like the INA125 or AD623 and proper shielding for the strain gauge circuit can help minimize noise.
    - Temperature Sensitivity: Strain gauges are highly sensitive to temperature variations, which can cause drift in readings.

      Solution: Incorporating temperature compensation elements, such as using foil strain gauges or integrated temperature compensation techniques, can help mitigate temperature-related errors.

4.2 Hardware Design and Circuit Challenges

1. Signal Amplification and Bandwidth

    - Limited Bandwidth: Many low-cost EMG systems suffer from limited bandwidth, leading to loss of high-frequency muscle activity signals.

      Solution: Choose high-quality instrumentation amplifiers with a broad frequency response, like INA333 or AD620, and carefully select filtering parameters to preserve important frequencies of muscle activity.

2. Power Supply and Stability

    - Power Supply Noise: Inaccurate or noisy power supplies can introduce fluctuations in signal processing, leading to errors in the final measurements.

      Solution: Use regulated power supplies and low-noise operational amplifiers for stable operation.
    - Limited Battery Life: Wearable systems often face issues with battery life as signal acquisition components like amplifiers and wireless modules consume significant power.

      Solution: Consider low-power electronics for signal processing and communication or use power-saving techniques such as duty cycling.

4.3 Calibration and Sensor Sensitivity Challenges

1. Calibration of Strain Gauge Systems [7]

    - Complex Calibration: Strain gauge systems require precise calibration with known forces (weights) to map the electrical signal to accurate force measurements. Miscalibration leads to significant errors.

      Solution: Implement multi-point calibration procedures and use calibration standards such as known weights or force transducers to ensure accurate measurements across a range of loads.

- Drift Over Time: Strain gauges can experience drift in their readings over time due to material fatigue or environmental changes.

  Solution: Regular recalibration of the system and use of feedback mechanisms to adjust for long-term drift.

2. sEMG Sensor Placement and Sensitivity

   - Inter-individual Variability: Different skin types, muscle structures, and electrode placements can lead to variability in sEMG signal strength and quality between individuals.

     Solution: Standardize electrode placement and use multiple reference sites to account for anatomical differences across subjects.

   - Skin Impedance: High skin impedance can lead to poor contact between electrodes and the skin, resulting in weak signals.

     Solution: Use pre-gelled or active electrodes with higher contact quality or apply conductive gels to improve skin-electrode coupling.

4.4 Data Integration and Synchronization Challenges

1. Synchronization of Multiple Signals [21]

   - Timing Mismatch: When combining sEMG and strain gauge data, synchronization between the two sensors is crucial to avoid errors in joint force and muscle activation analysis.

     Solution: Use a common time base for data acquisition and simultaneous sampling of both signals. Ensure that the sampling rate is high enough to capture rapid changes in both sEMG and force signals.

   - Data Fusion: Integrating data from multiple sensors (e.g., combining sEMG and force data) can be challenging due to differences in the nature of the signals.

     Solution: Use machine learning algorithms or sensor fusion techniques to integrate data streams and derive meaningful metrics, such as force-activation patterns.

5 Methodology

5.1 Key Steps of Implementation

1. Design and Setup of the Measurement System

   - sEMG Placement: A two-electrode surface EMG will be placed on the triceps brachii to record electrical muscle activity. [8]
   - Strain Gauge Integration: A strain gauge sensor will be attached to the gripping section of the weight to measure force variations during lifting and lowering. [26]

2. Data Acquisition and Signal Processing
    - Using biomedical signal acquisition hardware, I will collect real-time EMG and strain gauge signals. [27]
    - Noise filtering techniques (e.g., Butterworth or Notch filtering) will be applied to the sEMG signal to remove motion artifacts and powerline interference.
    - The strain gauge data will be calibrated to ensure accurate force measurement.
3. Analysis of Muscle Activation and Force Correlation
    - Extracting EMG Features: Root Mean Square (RMS), Mean Frequency (MNF), and Muscle Activation Time. [23]
    - Force-Movement Relationship: Comparing strain gauge data with EMG activation patterns to analyze how the triceps muscle contributes to lifting and lowering the weight. [24]
4. Testing and Validation
    - Conduct experiments with different loads to evaluate how the system performs under varying conditions.
    - Compare results with existing research to validate data accuracy.

5.2 Signal Specifications

Surface Electromyography (sEMG) Signal Specifications

1. Signal Characteristics
    - **Amplitude:**
        - The sEMG signal typically has an amplitude ranging from 1 µV to 5 mV for healthy muscles, depending on muscle activation level and sensor placement.
        - Resting Signal: Typically very low (< 0.5 mV).
        - Contracted Muscle: Can go up to several mV during intense muscle activity.
    - **Frequency Spectrum:**
        - The frequency content of sEMG ranges from 20 Hz to 500 Hz, with most useful information lying between 20-150 Hz.
        - Low-frequency components (20–50 Hz): Associated with slower muscle contractions and fatigue.
        - High-frequency components (100–500 Hz): Represent fast, high-intensity muscle contractions.
    - **Signal Noise and Artifacts:**

    - The sEMG signal is susceptible to motion artifacts, electrode movement, and powerline interference (50/60 Hz), which can distort data if not filtered.[8] [18]

2. Signal Processing
    - **Filtering:**
        - Bandpass filter (20–500 Hz) is used to retain relevant muscle signals.
        - Notch filter (50 or 60 Hz) to remove powerline interference.
    - **Feature Extraction:**
        - Root Mean Square (RMS): Used to quantify overall muscle activity.
        - Mean Frequency (MNF) and Median Frequency (MDF): Provide information on muscle fatigue.
        - Time Domain Features: Such as zero-crossing rate and number of peaks to analyze muscle contraction patterns.

Strain Gauge Signal Specifications

1. Signal Characteristics
    - **Amplitude:**
        - The strain gauge signal will be proportional to the force applied to the gripping section, typically in the range of 0 to 5 mV for small forces, and may go higher for larger forces (depending on the strain gauge calibration).
        - The voltage signal from the strain gauge is proportional to the strain and can be converted to force using the calibration factor.
    - **Frequency Spectrum:**
        - The strain gauge signals generally have a low-frequency range because the changes in force happen relatively slowly compared to muscle contractions.
        - Force-time response will be recorded at a lower sampling rate (500–1000 Hz).
    - **Signal Noise and Artifacts:**
        - Strain gauges are also prone to temperature drift and noise from external sources. Proper calibration and shielding can help minimize this. [26] [27]
2. Signal Processing
    - **Calibration:**
        - The strain gauge signal will need to be calibrated using known weights to establish the force-to-voltage conversion factor.
    - **Data Filtering:**
        - A low-pass filter (up to 50 Hz) may be applied to remove high-frequency noise.

Combined Signal Synchronization
Both sEMG and strain gauge signals will be synchronized in time to correlate muscle activity with the force applied during the movement. The synchronization is critical for analyzing the force-activation relationship during lifting and lowering. [24]

5.3 Measurement Parameters and Specifications

1. Surface Electromyography (sEMG) for Muscle Activation [8] [18]
   - Measured Parameter: Electrical activity of the triceps brachii muscle.
   - Unit: Millivolts (mV).
   - Sampling Rate: Typically 1000–2000 Hz to capture muscle activation accurately.
   - Filtering:
     - Notch Filter (50/60 Hz) – To remove powerline interference.
     - Bandpass Filter (20–500 Hz) – To retain relevant muscle signals and remove motion artifacts.
   - Feature Extraction:
     - Root Mean Square (RMS) – Measures overall muscle activation intensity.
     - Mean Frequency (MNF) – Indicates muscle fatigue and contraction characteristics.
2. Strain Gauge for Force Measurement [26] [27]
   - Measured Parameter: Force applied at the grip section of the weight.
   - Unit: Newtons (N) or Kilograms (kg).
   - Strain Gauge Type: Typically a foil-based Wheatstone bridge configuration for high sensitivity.
   - Sensitivity: Typically 2–5 mV/V depending on the gauge type.
   - Data Acquisition Rate: Around 500–1000 Hz, ensuring synchronization with EMG signals.
   - Calibration:
     - Using known weights to determine strain-to-force conversion.
     - Compensating for temperature and drift errors.
3. Additional Parameters (if applicable)
   - Forearm Angle Measurement (Optional): Using an IMU sensor (accelerometer + gyroscope) to analyze movement patterns.
   - Time Synchronization: Ensuring EMG and strain gauge data are aligned for precise correlation analysis.

Table 1: Specifications of Components and Example Devices/References

Component	Specification	Example Device/Reference
sEMG Electrodes	Bipolar, Ag/AgCl	Delsys Trigno, Olympus EMG sensors
Sampling Rate	1000–2000 Hz	[9]
Bandpass Filter	20–500 Hz	[18]
Strain Gauge Type	Foil-based Wheatstone bridge	Tekscan Grip, [26]
Strain Gauge Sensitivity	2–5 mV/V	[27]
Data Acquisition System	12-bit or 16-bit ADC	National Instruments, BIOPAC

5.4 Analog Circuit Design

5.4.1 Surface Electromyography (sEMG)

1. **Amplification stage**

   - istrumentation Amplifier Type:
     Low-noise instrumentation amplifiers are used to amplify the small sEMG signals, typically in the range of 1 μV to 5 mV. The choice of amplifier is crucial for maintaining signal integrity and minimizing noise.
   - Recommended Amplifiers:
     INA333 – Known for low noise and low offset, ideal for small signals like sEMG.
     - Input Impedance: > 10 $M\Omega$.
     - Noise Density: 0.9 $nV/\sqrt{Hz}$ at 1 kHz.
     - CMRR: > 100 dB.
     - Bandwidth: Adjustable for filtering at specific frequencies.

     AD620 – Offers adjustable gain and high common-mode rejection, suitable for noisy environments.
     - Input Impedance: 100 $M\Omega$.
     - Gain: Programmable (gain range 1 to 1000).
     - Noise Density: 0.5 $nV/\sqrt{Hz}$ at 1 kHz.
     - CMRR: > 100 dB.
   - Gain:
     The amplifier gain should be adjustable in the range of 1000 to 5000 to bring the signal within the range of the ADC.
   - Input Impedance:

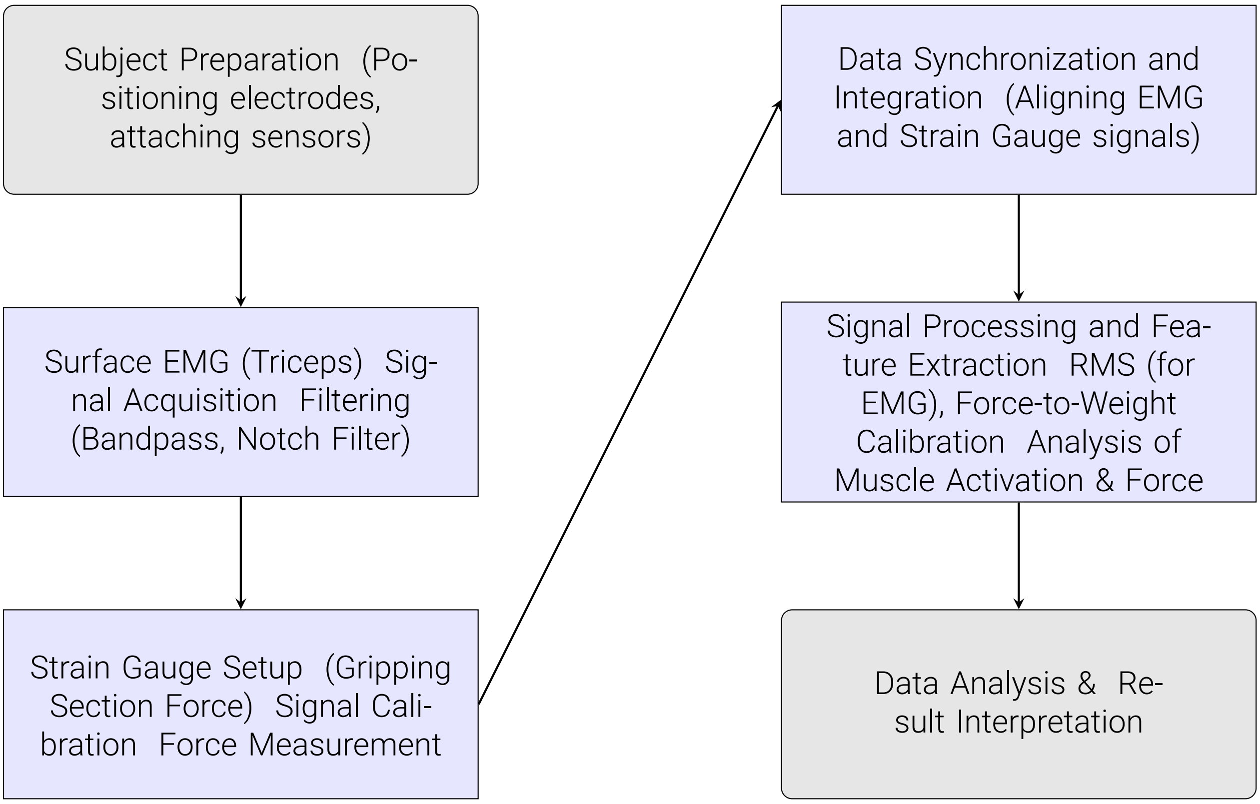


Figure 1: Flowchart of Measurement Setup for Forearm Movement Analysis

Should be high (> 10 $M\Omega$) to minimize signal distortion when interfacing with the skin and the electrodes.

- Common-Mode Rejection Ratio (CMRR):
  The amplifier should have a CMRR > 100 dB to effectively reject common-mode noise from surrounding electrical systems or the electrode-skin interface.

2. **BPF**
   A bandpass filter with cut-off frequency x-500 Hz to remove unnecessary signal.

3. **Notch filter**
   A Notch filter at 50 Hz is essential for removing powerline interference.

5.4.2 Strain Gauge Analog Circuit Requirements

1. **Strain Gauge Configuration**
   - A Wheatstone bridge configuration is used to measure small resistance changes from the strain gauge, which are then converted into measurable voltage signals.
   - Bridge Excitation Voltage: Provide a stable excitation voltage (typically 5V) to ensure accurate signal generation.

2. **Amplification stage**

   - Instrumentation Amplifier Type:
     An Instrumentation Amplifier is used to amplify the signal by a gain around 1000.

3. **Temperature Compensation**

   Include temperature compensation resistors to minimize drift due to temperature variations.

4. **Low-Pass Filtering**

   Use a low-pass filter (with a cut-off around 50 Hz) to remove high-frequency noise and ensure smooth force measurements.

5.4.3 Common Circuit Requirements for Both sEMG and Strain Gauge Systems

1. Power Supply

   - Use a dual power supply (e.g., ±12 V or ±5 V) to ensure stable operation of the amplifiers, filters, and other signal conditioning circuits.
   - It is essential to use a regulated supply to avoid signal distortion due to power fluctuations.

2. Analog-to-Digital Conversion (ADC)

   - ADC Resolution: A 16-bit ADC with a sampling rate of at least 1000 Hz is recommended to ensure high-resolution data for both sEMG and strain gauge signals.
   - Signal Digitization: Ensure that both sEMG and strain gauge signals are digitized synchronously to facilitate accurate force-activation analysis.

3. Signal Calibration

   Both the sEMG and strain gauge systems need to be calibrated using known references (e.g., standard weights for strain gauges and calibrated muscle activation levels for sEMG) to ensure accurate measurement and signal scaling.

Table 2: Final System Configurations

Component	**Specification**	**Example Model/Reference**
Instrumentation Amplifier	Low-noise, high CMRR	INA333, AD620
Strain Gauge Amplifier	Differential, adjustable gain	INA125, AD623
Notch Filter	50/60 Hz	Custom-designed or off-the-shelf filter ICs
High-Pass Filter	10-20 Hz	Butterworth or Sallen-Key filter

Component	**Specification**	**Example Model/Reference**
Low-Pass Filter	500 Hz (sEMG), 50 Hz (strain)	Butterworth or Chebyshev filter
ADC	16-bit resolution, > 1000 Hz sampling rate	ADS1115, MCP3208
Power Supply	±12 V or ±5 V	Linear or Switching Regulator

6 Introduction to Common Methods in the Design and Construction of Similar Systems

6.1 Surface Electromyography (sEMG) System Design and Methodologies

1. Electrode Placement and Sensor Selection [10]
   - Common Practice: The placement of surface electrodes over the motor point of the muscle (where the nerve enters the muscle) is a key factor in obtaining high-quality sEMG signals.
   - Active vs. Passive Electrodes:
     Active electrodes (e.g., ADInstruments or Noraxon systems) are more commonly used in recent studies due to their ability to amplify signals directly at the electrode, minimizing noise.
     Passive electrodes (e.g., Ag/AgCl) still appear in lower-cost or simpler setups.
2. Signal Amplification and Processing
   - Recent Advances: The use of low-noise instrumentation amplifiers and high-pass filters to improve the signal quality and remove unwanted artifacts has become standard.
   - Multi-Channel Systems: Systems with multiple channels allow for the measurement of sEMG from different muscles simultaneously, which is useful for analyzing complex movements.
     Example: Trigno wireless system by Delsys, which allows for multi-muscle sEMG recording.
3. Signal Processing and Feature Extraction [17]
   - Common Practices:
     Root Mean Square (RMS) for overall muscle activation.
     Time-frequency analysis techniques such as Wavelet Transform and Fourier Transform are used for extracting more detailed features, especially when studying muscle fatigue or different phases of muscle activity during dynamic movements.

- Recent Tools: Advanced signal processing techniques using Machine Learning for classification and prediction of muscle activity patterns.

6.2 Strain Gauge System Design and Methodologies

1. Strain Gauge Configuration [11]
    - Wheatstone Bridge: The Wheatstone bridge remains the most widely used method for converting strain into measurable voltage changes.
    - Strain Gauge Materials: Modern strain gauges use thin-film technology (e.g., Vishay foil strain gauges) for higher accuracy and temperature stability.
    - Integration: Strain gauges can be directly integrated into the gripping area of the weight or attached to a load cell for higher precision.
2. Signal Amplification
    - The signal from the Wheatstone bridge is typically small (in the mV range), and therefore requires high-precision instrumentation amplifiers (e.g., INA125, AD623).
    - Noise Filtering: Strain gauges typically require low-pass filters to smooth the signal and remove noise from the electrical environment. Modern systems often employ digital filtering alongside analog circuitry to ensure cleaner data.
3. Calibration and Force Measurement
    - Calibration: Strain gauges often require calibration with known weights to map voltage changes to force values accurately.
    - Load Cell Integration: In more advanced systems, strain gauges are integrated into load cells that can provide more precise and consistent force measurements, especially in systems where dynamic loading is expected.

6.3 Integration of sEMG and Strain Gauge Systems [28] [1]

1. Multi-Sensor Fusion
    - Recent Approaches: Combining sEMG and strain gauge data allows for a comprehensive analysis of muscle activity and force generation.
    - Real-time Feedback Systems: Wearable devices that combine sEMG signals and force data are increasingly popular for rehabilitation or sports science applications.

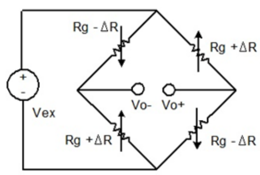
      Example: The Myoware muscle sensor used in combination with a strain gauge system for real-time muscle force estimation.
2. Signal Synchronization and Data Fusion

- Recent Methodologies: Data synchronization between sEMG and strain gauge systems is done using high-speed sampling techniques to ensure that both signals are aligned in time, allowing for meaningful analysis.
- Software Platforms: Platforms like LabVIEW or MATLAB are widely used for data synchronization and processing. These platforms allow for the integration of multichannel signals from both types of sensors and for the application of advanced analysis algorithms (e.g., Kalman filters, neural networks) for improved signal interpretation.

7 Methodology for Project Execution

In this section, we will outline the methodology for implementing the project, which involves the measurement of muscle activity and force using a combination of strain gauges and sEMG signals. The approach will follow a structured sequence of steps, including signal conditioning and analog-to-digital conversion (ADC). The sequence of components used in this implementation is as follows:

1. Wheatstone Bridge for Strain Gauge System
    - Role in the Implementation:
      The Wheatstone Bridge will serve as the initial signal conditioning circuit for the strain gauge used to measure the force during the movement of the weight. The bridge configuration converts the resistance change of the strain gauge (due to applied force) into a measurable voltage signal.
    - Working Principle:
      A strain gauge is attached to the gripping section of the weight. The resistance of the strain gauge changes when the weight is lifted or lowered, causing a differential voltage across the bridge.
      The Wheatstone Bridge will amplify the small voltage changes from the strain gauge, which is in the millivolt range, and make it suitable for further amplification and processing.
    - Importance in the Project:
      The Wheatstone Bridge is a critical component because it allows for accurate measurement of strain-induced voltage changes, ensuring that even small forces (e.g., during light lifting) are detected with high precision.



F3. Full Bridge

Figure 2: Full-Bridge

2. Band-Pass Filter (BPF) for Signal Conditioning

   - Role in the Implementation:

     After the strain gauge system has been modeled using the Wheatstone Bridge, the next step is to apply a Band-Pass Filter (BPF) to condition the signal further. The BPF allows us to isolate the relevant frequency range for muscle activity and force measurement, removing unwanted low and high-frequency noise.
   - Working Principle:

     The BPF will be designed to pass the frequencies associated with muscle contractions and force measurements (typically between 10 Hz and 500 Hz for sEMG signals and 0.1 Hz to 50 Hz for force signals from the strain gauge).

     It will filter out low-frequency baseline drifts and high-frequency noise that could interfere with accurate signal analysis.
   - Importance in the Project:

     The BPF ensures that only relevant data related to the muscle activity and force exertion during the weight lifting is passed on, improving the signal-to-noise ratio for the subsequent stages.

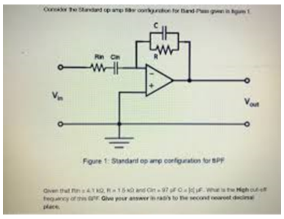


Figure 3: Band Pass Filter

3. Instrumentation Amplifier

   - Role in the Implementation:

     The Instrumentation Amplifier is used to amplify the signal coming from the strain gauge system (via the Wheatstone Bridge) and the sEMG system, ensuring that the small signals are boosted sufficiently for the next stages of processing.
   - Working Principle:

     The instrumentation amplifier will provide high input impedance and low output impedance while maintaining a high Common-Mode Rejection Ratio (CMRR) to reject noise from common sources (e.g., electrical noise or interference).

     This amplifier will boost the small signals coming from the Wheatstone Bridge (strain gauge) and sEMG signals, ensuring that they are in the optimal voltage range for processing.
   - Importance in the Project:

     The instrumentation amplifier plays a critical role in ensuring that low-amplitude signals from both the strain gauge and muscle activity (sEMG) are sufficiently amplified while maintaining the integrity of the signal by reducing common-mode interference.

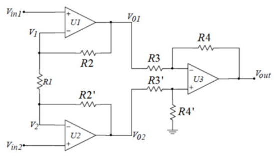


Figure 4: Instrumentation Amplifier

4. Notch Filter

    - Role in the Implementation:

      The Notch Filter is used to remove powerline interference at 50 Hz or 60 Hz, which is commonly found in environments with electrical devices. This is essential for obtaining clean signals from both the strain gauge and sEMG systems, as powerline interference can significantly distort the signal.

    - Working Principle:

      The Notch Filter will be designed to specifically attenuate the signal at the 50 Hz or 60 Hz frequency, which corresponds to the frequency of powerline noise.

      This filter will allow the rest of the signal frequencies (relevant to muscle activity and force) to pass through without significant attenuation.

    - Importance in the Project:

      By removing powerline interference, the Notch Filter ensures that the final signal contains minimal noise, improving the accuracy of the measurements and the overall data quality.

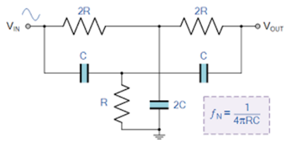


Figure 5: Notch-Filter

5. Analog-to-Digital Converter (ADC IC)

    - Role in the Implementation:

      The Analog-to-Digital Converter (ADC) will convert the processed analog signal from the strain gauge and sEMG systems into digital form that can be analyzed by a microcontroller or computer.

    - Working Principle:

      The ADC will sample the amplified and filtered signal at a high frequency (e.g., 1000 Hz or higher) and convert the signal to a digital output.

      The ADC will need to have sufficient resolution (e.g., 16-bit ADC) to capture the full range of muscle and force data accurately.

    - Importance in the Project:

The ADC is crucial because it allows for the digital representation of the signals, which can then be processed, stored, and analyzed using data acquisition software or real-time monitoring systems. The quality of the ADC directly influences the precision and accuracy of the final measurements.

7.1 Expected Outcomes

- A functional recording system capable of capturing muscle activity and force data in real-time.
- Identification of muscle activation patterns related to forearm movement.
- Insights into the biomechanics of weightlifting that can be applied to sports science, rehabilitation, and prosthetic development.

8 Overview of Software Used in Design and Simulation

In this section, we will provide an overview of the two key software tools used for design and simulation in this project: LTspice and Proteus. Both tools are essential for simulating the behavior of electronic circuits, specifically for the strain gauge system, signal processing, and analog-to-digital conversion aspects of the project.

LTspice [14]

LTspice is a powerful and widely used simulation software developed by Analog Devices (formerly Linear Technology). It is primarily used for simulating analog circuits, and its strengths lie in its ability to simulate high-frequency behavior, signal amplification, and feedback systems—all of which are critical for designing and testing the circuits in this project. Key Features:

- Analog Circuit Simulation: LTspice allows for the detailed simulation of analog circuits, which is essential for testing the behavior of strain gauge circuits, instrumentation amplifiers, and filtering systems.
- Transient Analysis: This feature is especially useful to observe how the system reacts over time, such as when lifting and lowering the weight.
- Frequency Domain Analysis: For simulating the performance of filters (e.g., Band-Pass Filter (BPF) and Notch Filter) in the frequency range relevant to muscle activity and force signals.
- Noise Analysis: LTspice provides tools to simulate and measure the effect of noise and interference, helping to ensure the signal quality after the amplification and filtering stages.
- Parameter Sweeps: It allows you to vary key parameters (e.g., resistor values, amplifier gains) to see how the circuit performs under different conditions, which is useful for optimizing circuit design before hardware implementation.

Application in the Project:

- Simulation of the Wheatstone Bridge: LTspice is used to simulate the Wheatstone bridge circuit with strain gauges, allowing for the verification of its response to different forces.
- Amplifier Design and Testing: The performance of the instrumentation amplifier and signal conditioning stages can be validated and optimized.
- Filtering and Signal Processing: The Band-Pass Filter (BPF) and Notch Filter designs can be tested to ensure that they are effective in removing unwanted noise and passing only relevant frequencies.

8.1 Configurations

1. Wheatstone Bridge Configuration:

   This is a basic configuration used to measure small changes in resistance (in this case, due to strain). The circuit consists of four resistors, with one of them being a strain gauge (with resistance R_G) that changes when strain is applied to it. [5] [4]

   $R_G \pm \Delta R_G$: The resistors representing the strain gauge (R_G) and the changes in resistance (ΔR) due to strain.

   V_{EX}: The excitation voltage supplied to the Wheatstone bridge.

   V_o: The output voltage that is proportional to the strain experienced by the system.

   The Wheatstone Bridge is designed so that the resistance changes in the strain gauge (ΔR) cause an imbalance in the bridge, which results in a measurable differential output voltage (V_o).

   - Strain Measurement:
     This Wheatstone bridge configuration is widely used to measure strain in materials, such as in load cells, pressure sensors, and force sensors.
   - Force Measurement:
     By applying a known force to the strain gauge, the resulting output voltage (V_o) can be correlated to the force applied, making it useful in mechanical testing and structural health monitoring.

2. BPF

   BPFs are commonly used in situations where you need to isolate signals within a specific frequency range, such as in radio communication, audio processing, and biomedical signal processing. [20] [3]

   Noise Reduction: In systems like EMG (electromyography), BPFs are used to isolate the muscle signal from noise and interference, ensuring that only relevant frequencies (like those corresponding to muscle contractions) are detected.

   The transfer function of a band-pass filter is typically represented as:

$$H(f) = \frac{f}{(f^2 - f_L^2)(f^2 - f_H^2)}$$

   Where:

- f is the frequency of the signal.
- f_L is the lower cutoff frequency defined by the high-pass filter.
- f_H is the upper cutoff frequency defined by the low-pass filter.

3. instrumentation

- Op-Amp Configuration:

  The circuit uses two operational amplifiers (U1 and U2) configured as inverting amplifiers, each working with a pair of resistors to control the gain and behavior of the system. [22]

  The two op-amps (U1 and U2) receive input voltages (V_{in1} and V_{in2}) that are processed and combined before passing through a second stage of op-amps (U3), which further amplifies or filters the signal.

- Components:

  (a) Resistors (R1, R2, R3, R4, and their primed versions R1', R2', R3', R4'): The resistors control the gain and frequency response of the filter. These resistors play a key role in defining the notch frequency and ensuring the filter effectively rejects a narrow band of frequencies.

  (b) Operational Amplifiers (U1, U2, and U3): The op-amps perform the necessary signal amplification and processing, allowing the filter to selectively attenuate frequencies around the notch frequency.

  (c) Notch Frequency: The circuit is designed to attenuate the signal at a specific frequency, which is often chosen to match the powerline frequency (50 Hz or 60 Hz) or other sources of unwanted noise. The exact notch frequency can be adjusted by carefully selecting the values for the resistors and capacitors (if any are added). [19]

- Working Principle:

  The first two op-amps (U1 and U2) provide initial signal amplification and conditioning, while the third op-amp (U3) is responsible for shaping the final output, ensuring that the desired frequencies are passed while the unwanted frequency (the notch frequency) is attenuated.

  The combination of the resistor network and op-amps allows the circuit to selectively target and filter out a specific frequency range without affecting the rest of the signal. [13]

4. Notch filter

- Basic Concept:

  A notch filter, also known as a band-stop filter, works by attenuating a narrow band of frequencies around a specific frequency (denoted as f_N), which is often the frequency of unwanted noise (such as powerline interference at 50/60 Hz). In this case, the circuit is designed to block this frequency while allowing others to pass through. [12]

- Circuit Components:
  (a) Resistors (R):
  Set the resistance levels that control the frequency response of the filter.
  (b) Capacitors (C):
  Work in tandem with resistors to define the filter's cutoff frequency.
  (c) 2R, C, 2C Configuration:
  This setup creates a parallel-resonant circuit, ensuring that only a specific frequency is attenuated.
- Working Principle:
  - The notch filter operates by having a resonant frequency at f_N, where the impedance of the circuit becomes very high, and the signal is effectively attenuated.
  - The circuit works by having two capacitors (C) and resistors (R), which determine the filter's response. The capacitors contribute to creating the resonant condition for the unwanted frequency to be attenuated. [20]
- Applications:
  - Powerline Noise Removal: A common use of this notch filter is to remove 50/60 Hz powerline interference in signals, which is particularly useful in sEMG or bioelectrical signal processing.
  - Audio Processing: It is also used in audio systems to remove unwanted frequencies such as hum or noise.
  - Communication Systems: Notch filters help to eliminate specific unwanted frequencies in RF (radio frequency) communication. [2]

9 Simulation and Results

9.1 Overall Review

In this Section we'll design and simulate needed sections of our sensor and amplifying circuit with necessary Filters ; We have also simulated the noise in the actual test path in order to bring the simulation closer to the original experiment in the real world.

We first take a look at final circuit with marked blocks ; then we explain each part of the circuit in full detail.

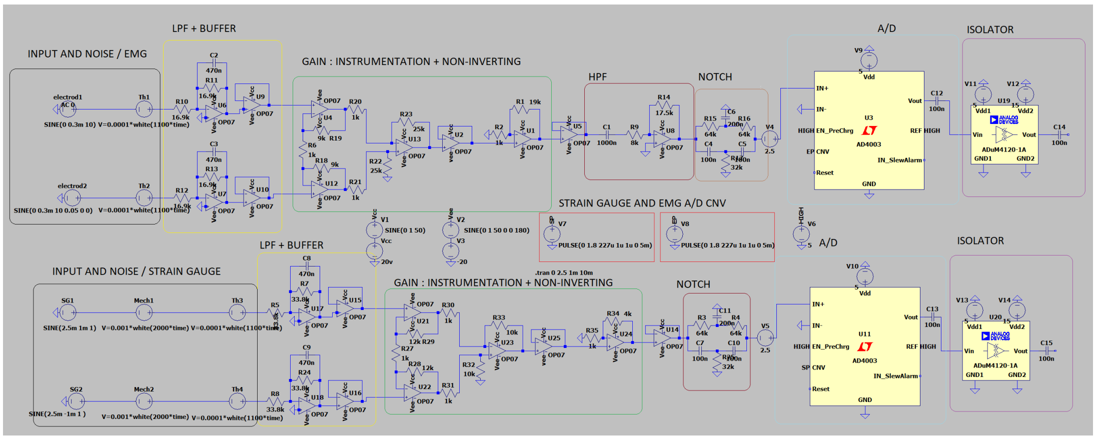


Figure 6: Circuit Block Diagram

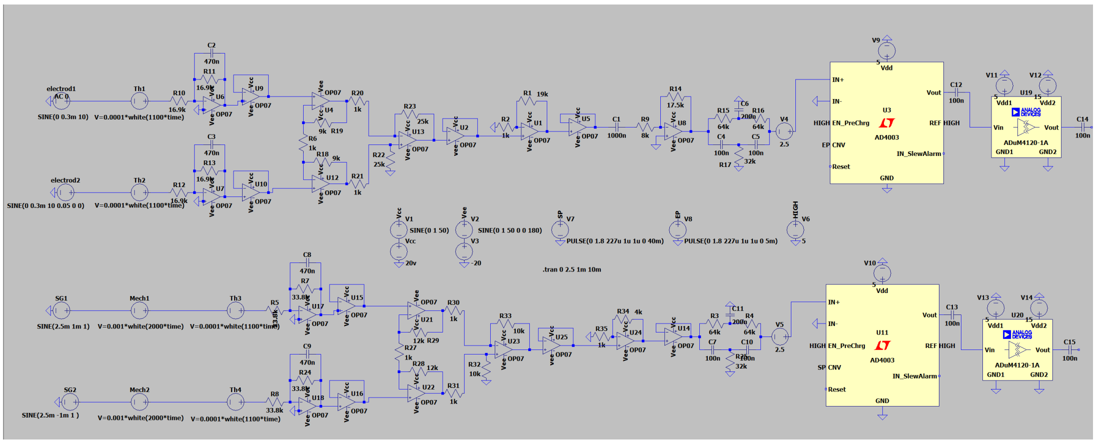


Figure 7: Circuit Full View

9.2 Input Signals & Noises

According to the explanations in the previous sections, the amplitude and frequency of each of the electromyogram and strain gauge simulation circuits have been selected as follows:

Table 3: Input Signals

Circuit	**Sample Frequency**	**Maximum Domian**
Strain Gauge	1Hz	2.5mV
EMG	10Hz	300uV

We have also considered the existing noises in the circuit as follows:

Table 4: Considered Noises

Noise Type	Strain Gauge	EMG
Mechanical Noise	1mV, $\approx 2000Hz$	-
Thermal Noise	0.1mV, $\approx 1100Hz$	0.1mV, $\approx 1100Hz$
Power Line Noise	1V, 50Hz	1V, 50Hz

You can see the schematic of this part of the circuit in the figures below:

1. **EMG:**

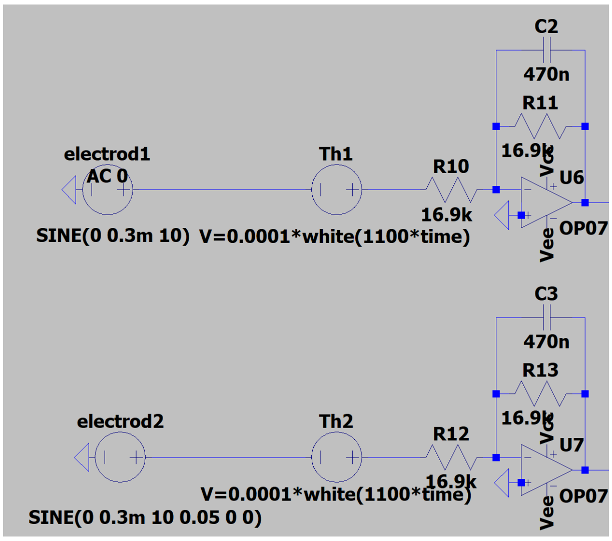


Figure 8: EMG Signals with Noise + Lowpass Filter

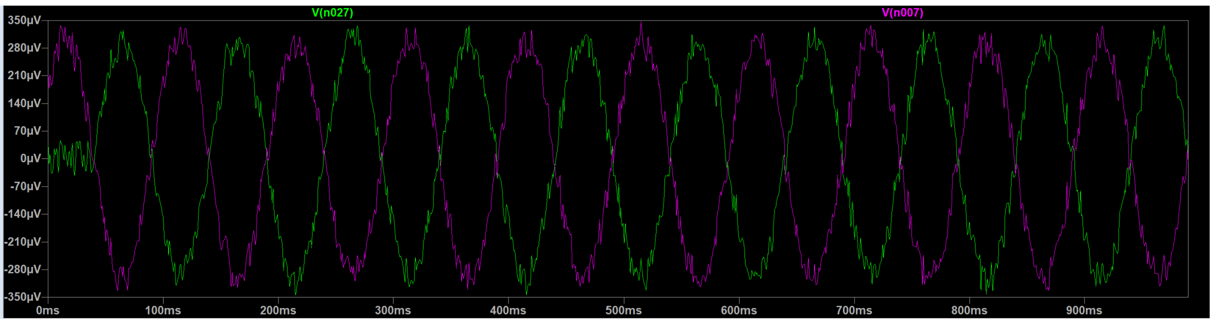


Figure 9: Two Noisy EMG Inputs Together

2. **strain gauge:**

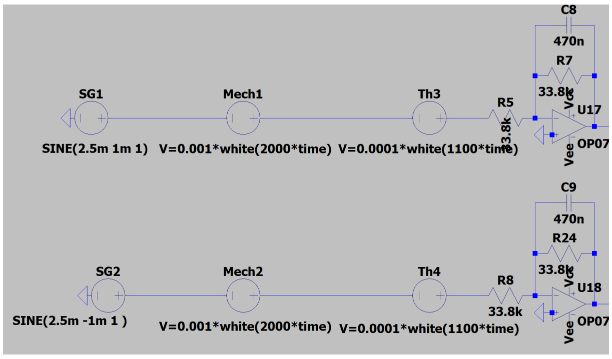


Figure 10: Strain Gauge Signals with Noise + Lowpass Filter

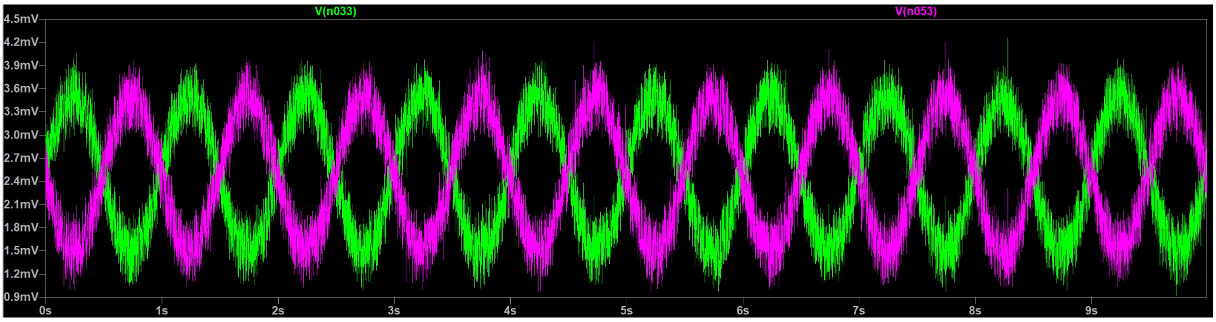


Figure 11: Two Noisy Strain Gauge Inputs Together

As you can see, we assumed that in each circuit, each input signal has a 180 degrees phase difference with the other input. Also, given that the strain gauge circuit has additional mechanical noise with a much higher relative amplitude (10 times) than the thermal noise, the input signal of the strain gauge process circuit has much more noise.

We note that the explanations of the low-pass filters in the schematic above are available in next sections.

9.3 Lowpass Filters

Given that the maximum frequency of our input signals is 10 Hz and the frequency of the existing noise is much higher, we expect that by applying a low-pass filter (with a small frequency margin for cutoff) before the amplification stage, the noise will be almost eliminated.

As seen in the circuit schematic in the previous section, we have used an active low-pass filter with feedback to avoid signal attenuation.

We know that the cut-off frequency of first order filters is given by :

$$f_{cut-off} = \frac{1}{2\pi RC}$$

For the EMG signal we have $f = 10Hz$ so we take $f_{cut-off} = 20Hz$. by this we calculate $R_L = 16.9k\Omega$ and $C_L = 470nF$. We also take the feedback resistor equal to filter resistor for unity gain.

For the strain Guage signal we have $f = 1Hz$ and we take $f_{cut-off} = 10Hz$. Again by calculation, we have $R_L = 33.8k\Omega$ and $C_L = 470nF$ and we take the feedback resistor equal to filter resistor for unity gain .

Now we observe the results of applynig these filters to our noisy signals :

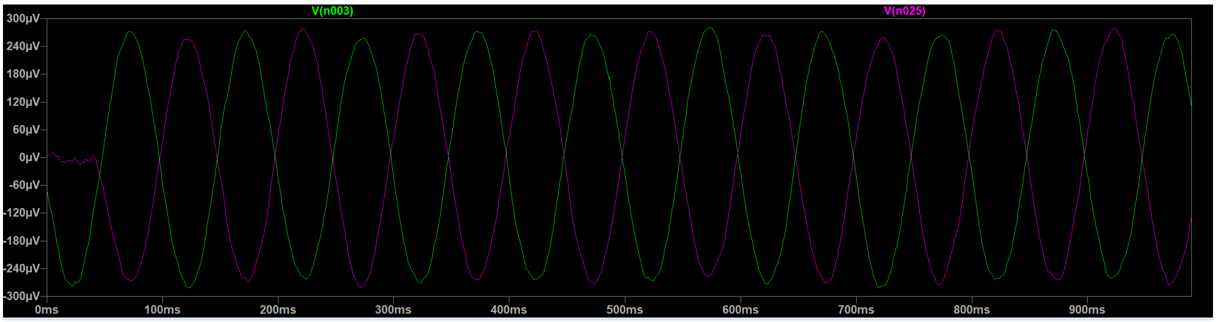


Figure 12: EMG Filtered Signal

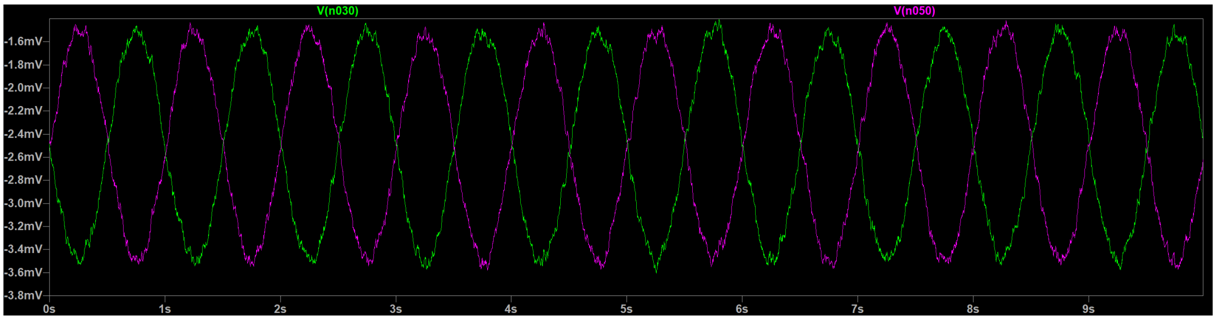


Figure 13: Strain Gauge Filtered Signal

As you can see, the EMG signal is almost without any noise. And as for Strain Gauge signal, most of the noise is eliminated.

9.4 Gain Stages

For better and more recognizable examination of the signals captured in reality, we need to amplify the signal. For this purpose, we use precision instrumentation amplifier stages with the ability to amplify the desired signal and also the ability to eliminate noise for the first gain stage, and also simple non-inverting amplification stages for the second gain stage.

The overview of an instrumentation amplifier and how to determine its gain is shown below:

$$V_{out} = \epsilon(\frac{R_4}{R_3})V_{cm} + (1 + \frac{2R_2}{R_1})\frac{R_4}{R_3}V_{diff}$$

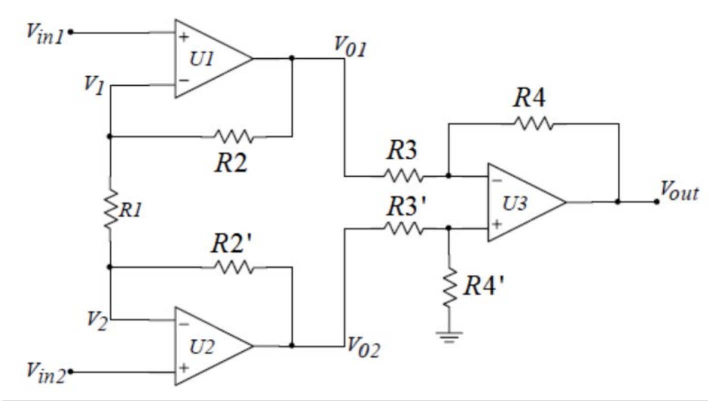


Figure 14: Instrumentation Amplifier

This class has flawless performance up to a maximum gain of 500.

For the remaining required gain we use a non-inverting amplifier with specified gain:

$$V_{out} = (1 + \frac{R_2}{R_1})V_{in}$$

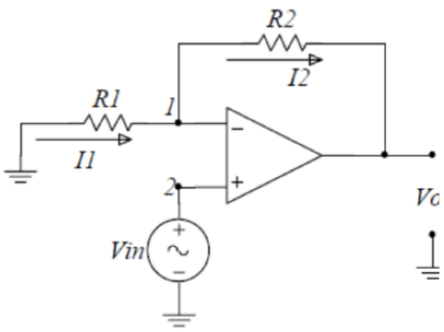


Figure 15: Non-Inverting Amplifier

First, we note that the final signal should have a maximum amplitude of $2.5V$ and should oscillate around zero.

In processing the EMG signal, the Highpass Filter after the gain stage will increase attenuation. In order to solve this, we amplify the signal to $5V$ amplitude and set the attenuation in a way to have a maximum $2.5V$ amplitude.

Since the strain gauge signal is low-frequency and does not require a high-pass filter, the signal will not be attenuated and the final amplitude will be obtained from the gain stage.

Now we take a look at the diffrential input of our Gain Stages and calculate the values of our elements:

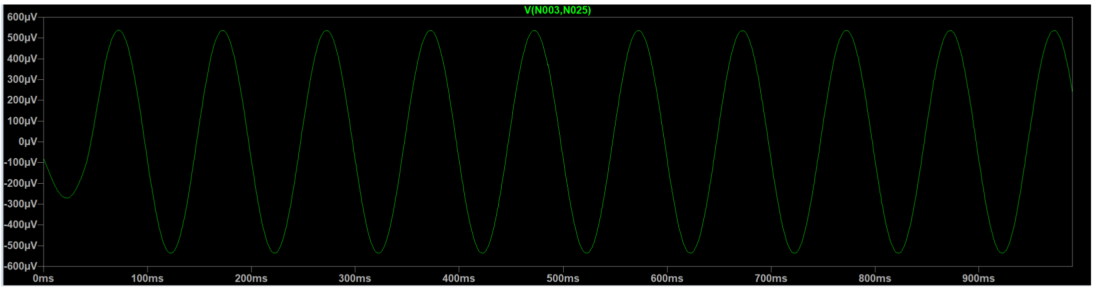


Figure 16: EMG Diffrential Amplifier Input

As you can see, for EMG signal, the amplitude of the input to the Apmlifier is about $500\mu V$ so to reach an amplitude of $5V$, we need a Gain around 10000. To achieve this, we use a 500 instrumentation gain and a 20 non-inverting stage gain.

Therefore, the values of instrumentation Resistors will be:

$$R_1 = R_1' = 1k\Omega$$
$$R_2 = R_2' = 9k\Omega$$
$$R_3 = R_3' = 1k\Omega$$
$$R_4 = R_4' = 25k\Omega$$

And for non-inverting amplifier:

$$R_1 = 1k\Omega$$
$$R_2 = 19k\Omega$$

Now:

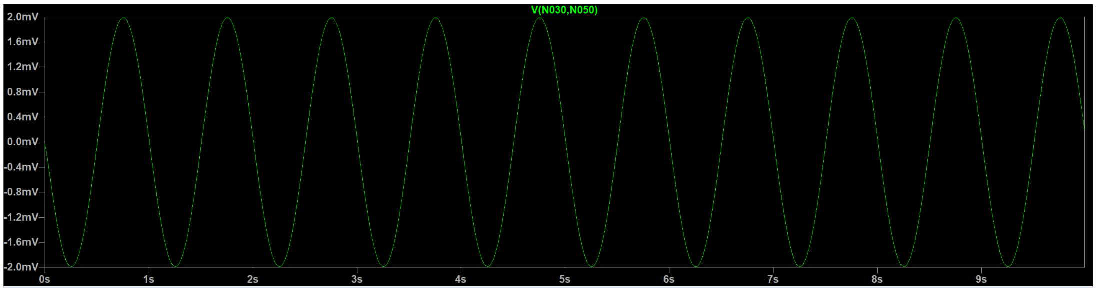


Figure 17: Strain Gauge Diffrential Amplifier Input

You can see that for the Strain Gauge, signal amplitude at the input of the apmlifier is around $2mV$. To reach the desired $2.5V$ amplitude, we need a Gain around 2500. We will achieved this by using a 500 instrumentation gain and a 5 non-inverting stage gain.

Therefore the values of the instrumentation resistors will be:

$$R_1 = R_1' = 1k\Omega$$
$$R_2 = R_2' = 12k\Omega$$
$$R_3 = R_3' = 1k\Omega$$
$$R_4 = R_4' = 10k\Omega$$

And for the non-inverting amplifier:

$$R_1 = 1k\Omega$$
$$R_2 = 4k\Omega$$

The final diagram of the amplification circuits is as follows:

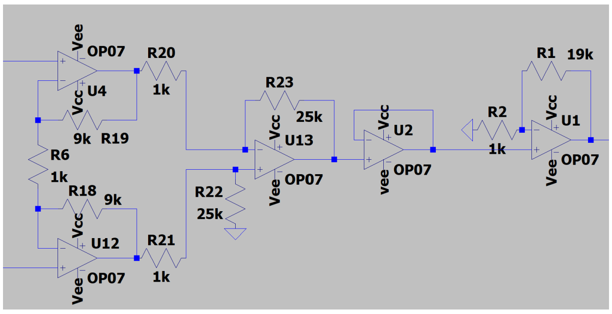


Figure 18: EMG Signal Amplifier

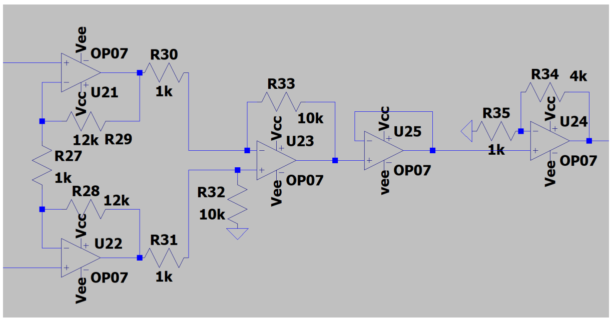


Figure 19: Strain Gauge Signal Amplifier

We now check the output of the Amplifiers:

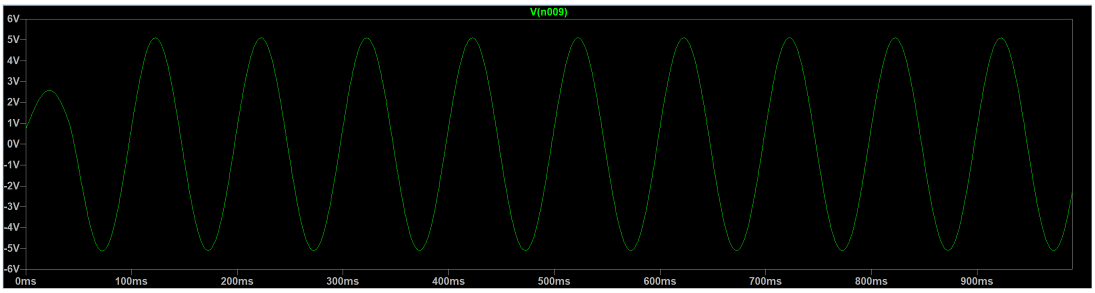


Figure 20: EMG Amplified Signal

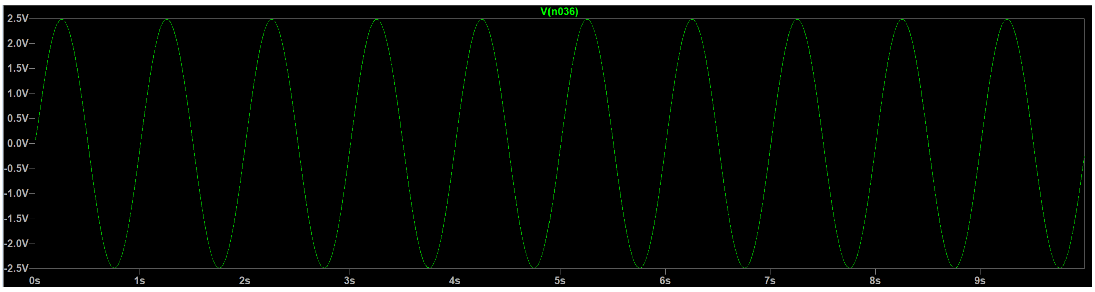


Figure 21: Strain Gauge Amplified Signal

These results are aligned to our expectations.

9.5 Highpass Filter

As we mentioned in 9.4, since the Strain Gauge signal is a mechanical signal with low frequency, Highpass filter is not needed here. But we still need an active highpass filter for EMG circuit with a cut-off frequncy of 1Hz.

The design of our HPF:

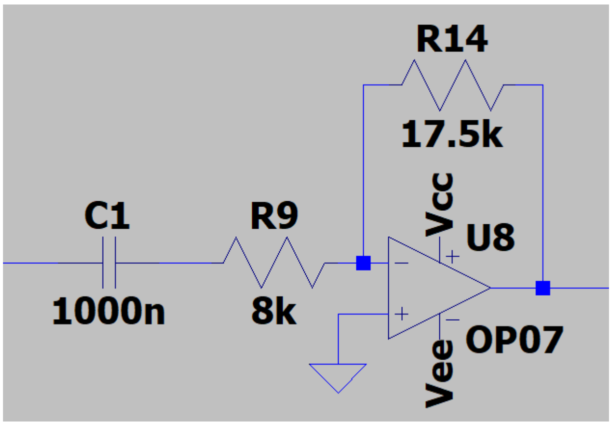


Figure 22: Highpass Filter

The feedback of this filter is set in a way to achieve an amplitude of $2.5V$ after the notch filter.

9.6 Notch Filter

A **notch filter** is a type of band-stop filter that is designed to attenuate a very narrow frequency range while allowing other frequencies to pass. In our circuit, we use a notch filter to suppress **power line interference** at 50 Hz (or 60 Hz, depending on the region). Power line noise can couple into our system through electromagnetic interference (EMI) or improper grounding, affecting the accuracy of Strain Gauge and EMG signals. By applying a notch filter, we effectively remove this unwanted component while preserving the desired signal characteristics.

A Twin-T notch filter is designed below:

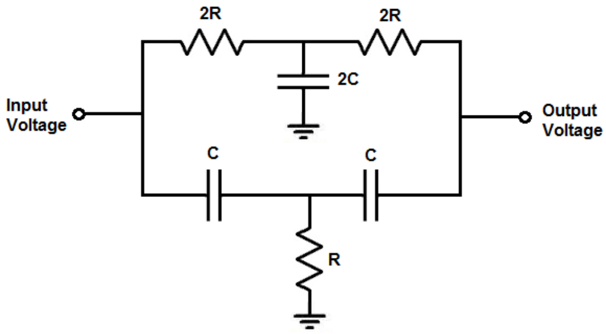


Figure 23: Notch Filter

And the Removed frequency is given by:

$$f_{cut-off} = \frac{1}{2\pi RC}$$

We choose the values of R and C to remove the frequency of polwer line noise (50 Hz):

$$R = 32k\Omega$$
$$C = 100nF$$

Here is the implementation of this part, using LTSpice:

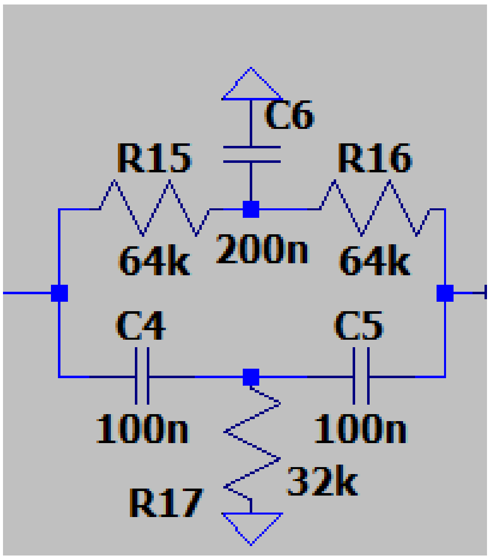


Figure 24: Notch Filter Circuit

Now we take the outputs of both signals which we expect to be between $-2.5V$ and $2.5V$ without any noise:

Again, You can see that these results are aligned to our expectations.

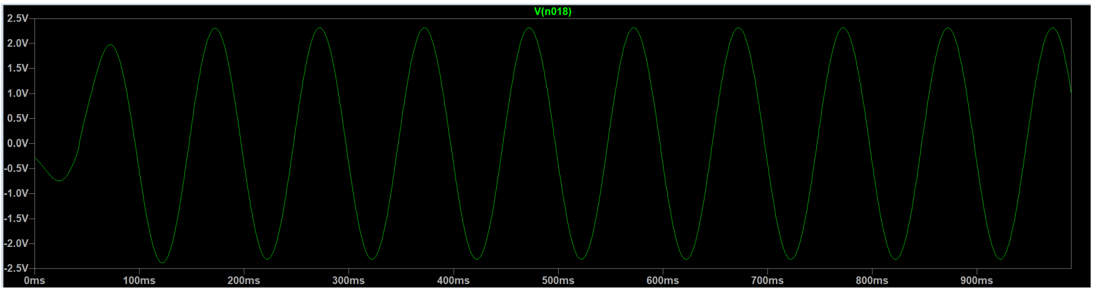


Figure 25: EMG Final Analog Signal

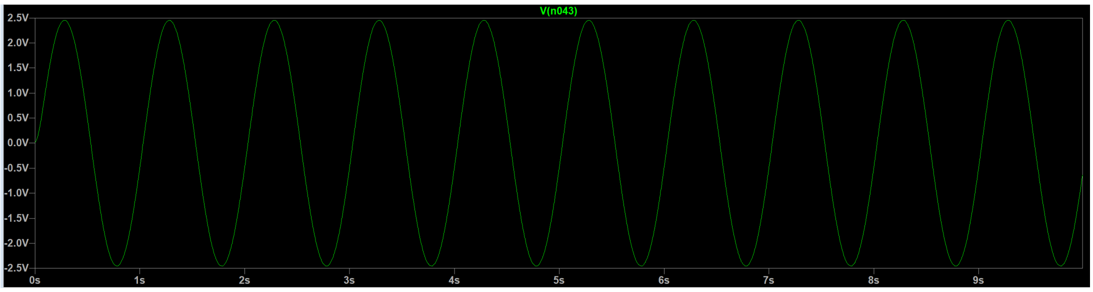


Figure 26: Strain Gauge Final Analog Signal

9.7 Buffer

A **buffer** (typically implemented using an operational amplifier in a voltage follower configuration) is used to provide **impedance matching** and **signal isolation**. In our circuit, the buffer ensures that the high-impedance output of the strain gauge or EMG sensor is not loaded by the next stage of signal processing. This prevents signal distortion and preserves the original waveform. Additionally, the buffer acts as a **current amplifier**, allowing the subsequent stages to receive a stable and undistorted voltage signal.

We use buffer to connect any two stages which may affect each others performance. The design of our buffer circuit is shown below:

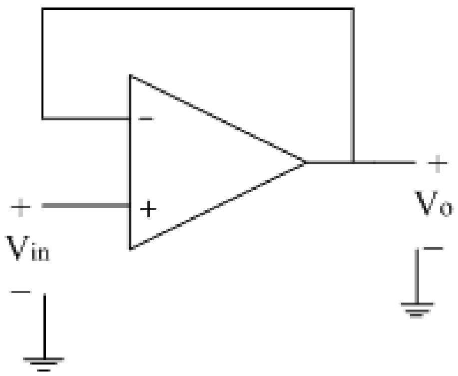


Figure 27: Buffer Design

9.8 Analog to Digital Convertor

An **Analog-to-Digital Converter (ADC)** is used to convert the continuous-time analog signals from the strain gauge and EMG sensor into discrete-time digital signals for further processing. This is necessary because most modern data analysis and signal processing techniques require digital signals that can be processed by microcontrollers or computers.

Why We Use A/D Conversion

1. Microcontrollers and digital signal processors can only process digital signals.
2. Digital signals are less susceptible to noise compared to analog signals.
3. Digital data can be easily stored and transmitted without degradation.
4. Digital signal processing (DSP) techniques such as filtering, feature extraction, and machine learning can be applied.

How We Use A/D Conversion

The ADC (such as the **AD4003**) takes an input voltage within a specified range (e.g., $0V$ to $5V$) and converts it into a digital value.

Proper selection of the ADC reference voltage (**REF =** $5V$) ensures that the input signal is mapped correctly within the ADC's dynamic range.

The Design of A/D Stage in Spice:

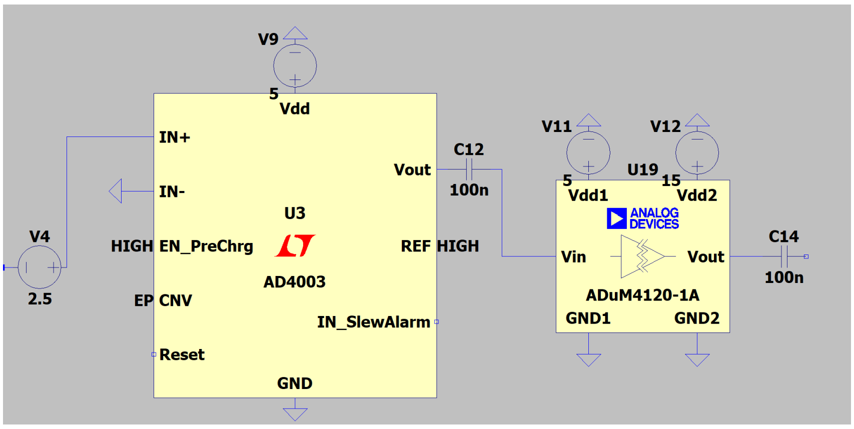


Figure 28: A/D + Isolator Design

The CNV pin connects to a pulse that determines the sampling rate of A/D. To sample the signal at proper times, the time period of this pulse is chosen this way:

EMG A/D : $5ms$

Strain Gauge A/D : $50ms$

Now we know that our final analog signals have a range of $-2.5V$ to $2.5V$. So in order to reach the 0 to $5V$ range, we shift the A/D Stage input by $2.5V$.

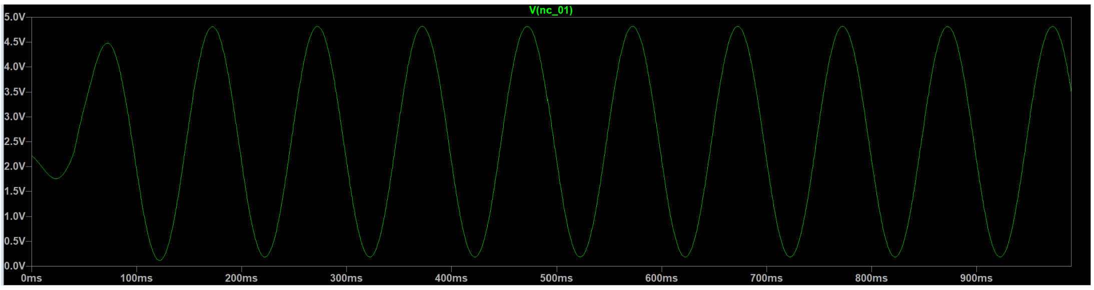


Figure 29: EMG A/D Input

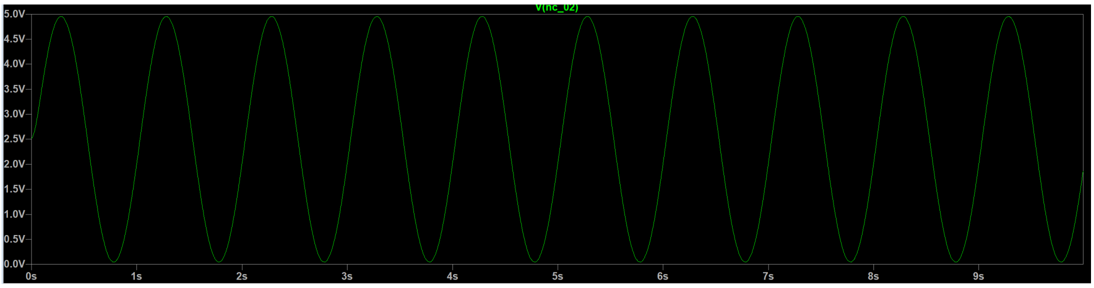


Figure 30: Strain Gauge A/D Input

After a long process the outputs would be:

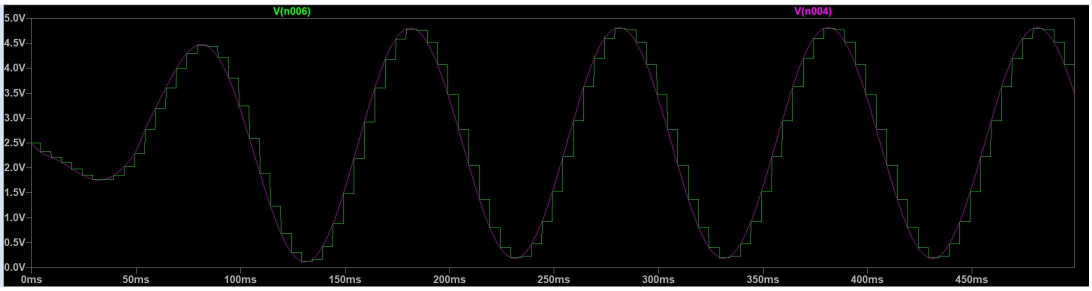


Figure 31: EMG Quantized Signal

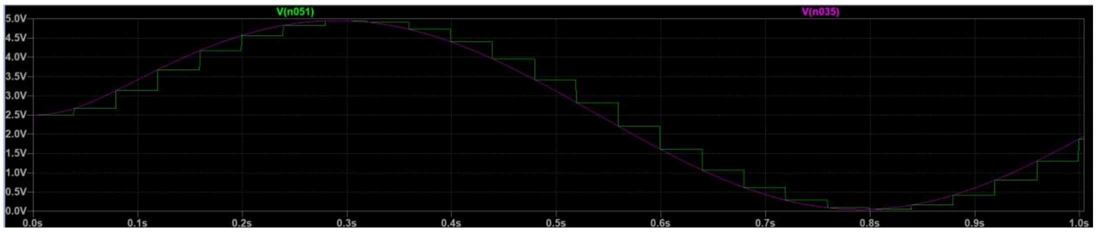


Figure 32: Strain Gauge Quantized Signal

9.9 Isolator

An **isolator** is used in our circuit to electrically separate different sections while allowing signal transmission. This is crucial for safety, noise reduction, and preventing unwanted interference.

We place an isolator between the sensor circuit and the processing unit (e.g., microcontroller or ADC).

In our circuit, an isolator ensures reliable signal transmission without direct electrical connection, enhancing both performance and safety.

The Design of the isolator in our simulation is shown in 28.

We expect the output of the isolator to be the same with A/D output:

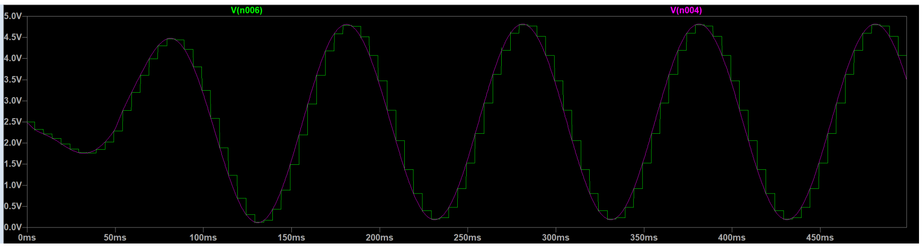


Figure 33: EMG Isolator Output

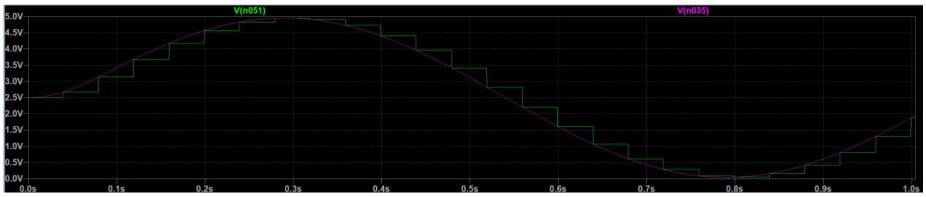


Figure 34: Strain Gauge Isolator Output

You can see that these results are aligned to our expectations.

10 Conclusion

This project successfully developed a biomechanical recording system that integrates strain gauge sensors and surface electromyography (sEMG) for analyzing forearm movement during weightlifting exercises. The combination of these two systems allowed for the precise measurement of muscle activation in the triceps brachii and the force exerted at the gripping section of the weight. The design faced several challenges, such as signal noise and the need for accurate calibration of both systems. However, through the application of effective filtering techniques and proper signal conditioning, reliable data was acquired. The outcomes of this project contribute significantly to understanding forearm biomechanics and have potential applications in areas such as sports science, rehabilitation, and prosthetic device development. Future work could focus on optimizing the system for wireless communication and real-time data processing, as well as integrating machine learning algorithms to enhance the analysis of muscle-force relationships during dynamic movements.

11 References

References

[1] S. Amini et al. "Real-time data fusion from sEMG and strain gauges for muscle force estimation in wearable devices". In: *IEEE Transactions on Biomedical Engineering* 70.12 (2023), pp. 3521–3531.

[2] Authors. "Application of Notch Filters in Signal Processing". In: *IEEE Xplore Journal* 52.3 (2004), pp. 1080–1086.

[3] Authors. "Band-Pass Filters and Their Applications in Biomedical Engineering". In: *IEEE Transactions on Biomedical Engineering* 37.5 (1990), pp. 484–489.

[4] Authors. "Introduction to Strain Gauges and Their Applications". In: *Sensors and Actuators A: Physical Journal* 19.3 (1989), pp. 143–149.

[5] John P. Bentley. *Principles of Measurement Systems*. 4th. Pearson, 2005.

[6] F. Boudrika et al. "Assessing the impact of noise and cross-talk on the performance of wearable sEMG systems". In: *IEEE Access* 10 (2022), pp. 12534–12542.

[7] Y. Chen et al. "Innovations in wearable multi-sensor systems for real-time force and muscle activity monitoring". In: *Journal of Neural Engineering* 19.4 (2022), p. 045007.

[8] C. J. De Luca. "Electromyography signal processing and applications". In: *Journal of Biomechanics* 39.3 (2006), pp. 367–375.

[9] C. J. De Luca. "The use of surface electromyography in biomechanics". In: *Journal of Applied Biomechanics* 13.2 (1997), pp. 135–163.

[10] A. J. Fradkin et al. "Application of surface electromyography for muscle fatigue analysis during dynamic movements". In: *Journal of Sports Science & Medicine* 19.1 (2020), pp. 35–45.

[11] S. Gagnière et al. "Design and implementation of a high-precision strain gauge system for force measurement in biomechanics". In: *Sensors* 21.4 (2021), p. 1245.

[12] W. E. L. Gribbon and M. F. Jamieson. *Electronic Filters: Theory and Practice*. John Wiley & Sons, 1988.

[13] R. S. Karris. *Design and Application of Analog Filters*. 2nd. Pearson, 2011.

[14] Kenneth Kundert. *LTspice IV: A Designer's Guide*. NUN, 1995.

[15] R. Merletti and D. Farina. *Surface electromyography: Physiology, engineering, and applications*. IEEE Press, 2016.

[16] R. Merletti and D. Farina. *Surface electromyography: Physiology, engineering, and applications*. IEEE Press, 2016.

[17] A. Phinyomark et al. "A survey of electromyography signal processing techniques". In: *Biomedical Signal Processing and Control* 42 (2018), pp. 51–69.

[18] A. Phinyomark et al. "Feature extraction and selection for myoelectric control based on wearable EMG sensors". In: *Sensors* 12.9 (2012), pp. 12461–12490.

[19] Paul Scherz and Simon Monk. *Practical Electronics for Inventors*. 4th. McGraw-Hill Education, 2016.

[20] R. J. Schilling and D. L. Harris. *Analog Filter Design*. 1st. PWS Publishing, 1996.

[21] M. R. Smith et al. “Wearable EMG and force sensors for real-time muscle activity monitoring during dynamic movements”. In: *IEEE Transactions on Biomedical Engineering* 70.7 (2023), pp. 2335–2345.

[22] M. E. Van Valkenburg. *Analog Filter Design*. 2nd. Oxford University Press, 2000.

[23] P. Välkkynen et al. “Signal processing in electromyography and force measurement systems”. In: *Biomedical Engineering* 62.3 (2015), pp. 138–146.

[24] A. D. Vigotsky et al. “Biomechanical perspectives on measuring muscle activation with electromyography”. In: *European Journal of Applied Physiology* 118.4 (2018), pp. 889–910.

[25] Z. Wang et al. “Challenges in strain gauge systems for biomechanical force measurement: Calibration and drift issues”. In: *Sensors* 21.3 (2021), pp. 745–755.

[26] D. A. Winter. *Biomechanics and motor control of human movement*. John Wiley & Sons, 2009.

[27] Y. Yang et al. “A wearable force-sensing glove for monitoring hand movements”. In: *Sensors* 18.5 (2018), p. 1405.

[28] S. Zhang et al. “Wearable multi-sensor systems for monitoring muscle activity and force during human movement”. In: *Sensors* 22.7 (2022), p. 2354.

A Appendix A: DataSheets

Below is a link to download the AD620 data sheet:
AD620 data sheet
Below is a link to download the INA333 data sheet:
INA333 data sheet