Design of electromyographic and electrocardiographic signals conditioning circuit

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***Abstract*—This paper presents a novel approach to designing a signal conditioning circuit for electromyography (EMG) and electrocardiography (ECG), focusing particularly on evaluating the morphophysiological characteristics in individuals aged 15 to 40 years and their influence on data acquisition. It integrates engineering and morphophysiology knowledge, exploring error correction techniques and muscle interactions during movements. The practical integration of EMG and ECG sensors into prosthetic limb control systems is described, along with an innovative methodology for recording simultaneous EMG signals from arm muscles and cardiac signals. Additionally, a manual calibration system is proposed to enhance signal fidelity, accommodating morphophysiological variations among individuals. This interdisciplinary study offers significant implications for rehabilitation and assistive technology, addressing the unique needs of individuals within the specified age group in EMG signal processing and prosthetic development.**

I. INTRODUCTION

Signal conditioning circuits for electromyography (EMG) and electrocardiography (ECG) play a critical role in enhancing the accuracy and reliability of data acquisition for various biomedical applications. Despite significant advancements in this field, challenges remain in achieving high-fidelity signal acquisition, especially in environments with substantial noise and interference. This paper presents a novel approach to the design of signal conditioning circuits for EMG and ECG, focusing specifically on individuals aged 15 to 40 years. This age range is chosen due to its broad representation of active, healthy individuals who are often the primary users of prosthetic and rehabilitation technologies.

Previous studies have separately explored EMG and ECG signal processing, but the integration of both types of signals into a cohesive system for prosthetic control remains underdeveloped. By leveraging a synthesis of engineering principles and morphophysiological insights, this study addresses gaps in current methodologies, particularly the need for improved error correction techniques and a deeper understanding of muscle dynamics during movement. This dual focus on EMG and ECG is crucial because it allows for comprehensive monitoring of both muscular and cardiac functions, which is essential for developing more responsive and adaptive prosthetic devices.

The investigation incorporates a diverse array of research insights, delving into aspects of EMG and ECG signal processing relevant to their integration into prosthetic control systems. It discusses automated error correction methodologies employing deep metric learning frameworks, which are essential for precise human-machine interfacing in noisy or multivariate recording environments. The study also details the integration of EMG and ECG sensors into prosthetic limb control systems, augmented with tactile and position sensors to provide vital sensory feedback.

A comprehensive signal acquisition and conditioning system is outlined, comprising instrumentation amplifiers, active bandpass filters, amplifiers, rectifiers, and microcontrollers, all tailored to achieve fine control and feedback in prosthetic limbs. Additionally, an innovative methodology for simultaneously recording EMG signals from arm muscles and cardiac signals is introduced, offering potential applications in pathology detection and prosthesis design targeted at the specified age group.

Addressing the inherent challenges posed by interference and noise in EMG signal acquisition, the paper proposes an manual-calibration system to enhance signal fidelity and reliability. By adopting high-resolution systems and advanced filtering techniques, the goal is to elevate signal quality for efficient feature extraction and classification, which is crucial for effective prosthetic control and rehabilitation applications. Importantly, the study considers morphophysiological variations among patients within the specified age group, ensuring that the solutions are adaptable and responsive to individual needs.

II. GENERAL OBJECTIVE

To design a signal conditioning circuit for ECG and EMG signals, enabling precise and reliable acquisition and processing of electrical signals from the heart and muscles, considering morphophysiological characteristics for accurate clinical and research interpretation.

III. SPECIFIC OBJECTIVES

- Investigate and select appropriate electronic components for the acquisition of ECG-EMG signals, considering individual morphophysiological variations such as skin impedance, heart morphology, and muscle distribution, to ensure optimal capture of biological signals regardless of differences among subjects.
- Design and implement a signal conditioning circuit that integrates adaptation and customization techniques, such as manual gain adjustment and dynamic filter selection, to adapt to the specific morphophysiological characteristics of each individual and maximize the quality of the acquired signals.
- Evaluate the performance of the designed circuit through experimental tests that include the acquisition of ECG-EMG signals in a diverse population, representative of human morphophysiological variations. The aim is to

determine the effectiveness of the circuit in preserving the integrity of biological signals and its ability to provide reliable and consistent data regardless of individual differences. Specifically, the sensitivity of the circuit should fall within the range of 90-95%, ensuring high accuracy and reliability in signal detection and analysis.

IV. THEORETICAL FRAMEWORK

A. Morphophysiological characteristics influencing EMG-ECG data acquisition

B. Heart

The heart serves as the central component of the cardiovascular system, responsible for generating the ECG signal. Any anomalies in its structure or function, such as heart diseases, arrhythmias, or myocardial damage, can profoundly influence the shape and magnitude of the recorded ECG signal. Within the autonomic nervous system lie the sympathetic and parasympathetic systems, regulating cardiac activity. While sympathetic tone elevates heart rate and contractility, parasympathetic tone exerts opposite effects, and fluctuations in the activity of these systems, particularly during periods of stress or relaxation, can induce changes in the recorded ECG signal. The histological and anatomical composition of the myocardium plays a crucial role in its capacity to generate and propagate electrical impulses, and any alterations in cellular morphology or the alignment of myocardial fibers can affect the ECG signal by modifying electrical conduction patterns. Fundamental to blood circulation and ECG signal generation is myocardial contraction. Any disruptions in contractile function, such as systolic or diastolic dysfunction, can manifest as deviations in the ECG signal, and regulation of cardiac muscle contraction physiology involves intrinsic and extrinsic mechanisms. Changes in ion concentration, calcium sensitivity, or autonomic nervous system activity can impact the ECG signal by altering heart contractile activity.[2]

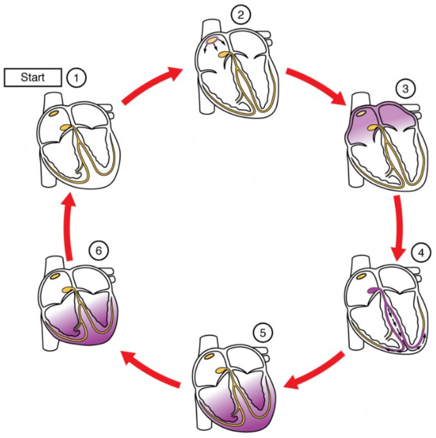

Figure 1. Heart contraction

Cardiac output, defined as the volume of blood ejected by the heart per minute, can influence tissue perfusion and subsequently alter the heart's electrical activity, as recorded by the ECG. The initiation of the cardiac beat stems from the depolarization of the sinoatrial node, which generates the electrical impulse propagating through the heart, and any disturbances in impulse generation or conduction can disrupt the recorded ECG signal. Variations in the morphology and duration of ECG waves and complexes may signify normal or abnormal cardiac conditions, and accurate interpretation of the ECG necessitates a thorough understanding of cardiac anatomy and physiology.

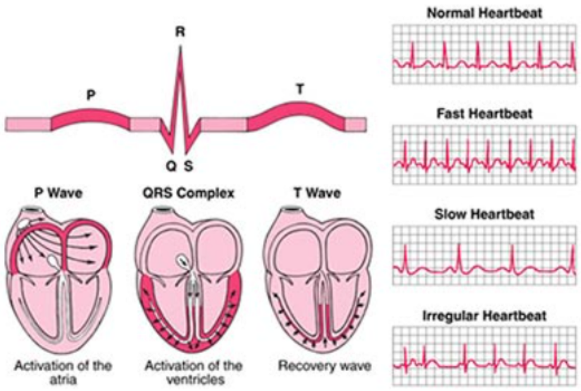

Figure 2. ECG

The structure and function of blood vessels, encompassing arteries, veins, and capillaries, can affect vascular resistance and blood flow distribution, potentially impacting the ECG signal, and regulated by autonomic nervous system activity and local metabolic demands, the distribution of blood flow among different organs and tissues can influence cardiac electrical activity and, consequently, the ECG signal. Physical principles governing blood flow, such as Poiseuille's law and Ohm's law, can influence vascular resistance and blood pressure, thereby impacting the recorded ECG signal, and arterial and venous pressures serve as pivotal determinants of tissue perfusion and cardiac function, with variations potentially altering the ECG signal by modifying heart workload and coronary circulation. Regulation of fluid and solute exchange across capillary membranes, governed by hydrostatic and colloid osmotic pressures, can affect blood flow distribution and consequently the ECG signal, while neuro-hormonal regulation, including autonomic nervous system activity and hormone release, can influence cardiac and vascular function, thereby manifesting in the ECG signal. Circulation to vital organs like the brain, liver, and heart is meticulously regulated to sustain tissue perfusion and cellular function, with disruptions potentially affecting the ECG signal, and the composition and characteristics of blood, including hemoglobin concentration, blood cell types, and Rh factors, can impact cardiovascular function and, consequently, the ECG signal.[24]

C. Memory and learning

Memory and learning, intricate cognitive processes, involve the acquisition, retention, and retrieval of information. These processes extend beyond the brain, eliciting physiological and emotional responses across the body, encompassing the heart and muscles. Throughout learning and memory formation, synaptic connections between neurons are established and fortified, influencing neuronal activity in regions governing autonomic regulation, pain perception, and emotional response. Consequently, these neural changes can impact cardiac and muscular activity, as observed in EMG and ECG recordings. Furthermore, memory and learning can evoke autonomic responses, such as fluctuations in heart rate, blood pressure, and muscle activity. For instance, anticipation of stressful or exhilarating events can activate the sympathetic nervous system, precipitating heightened heart rate and alterations in muscle activity discernible through EMG measurements. Moreover, conditioning and association formation during the learning process can induce physiological changes. Associations between conditioned stimuli and emotional responses may trigger shifts in cardiac and muscular activity, elucidated by alterations in ECG and EMG signals, thereby providing insights into the physiological correlates of learning and memory. Additionally, emotional experiences intertwined with memory formation can profoundly affect cardiovascular and muscular dynamics. Instances of stress, anxiety, or emotional arousal can elicit autonomic changes impacting ECG and EMG signals. These fluctuations encompass heightened heart rate and variations in muscle tension, both of which are discernible through these monitoring techniques.

D. Pain

The central nervous system (CNS) plays a pivotal role in pain perception and modulation, regulating neural pathways that transmit pain signals from peripheral receptors to the brain. These pathways are governed by specific CNS regions, including the spinal cord, brainstem, and higher cortical areas.

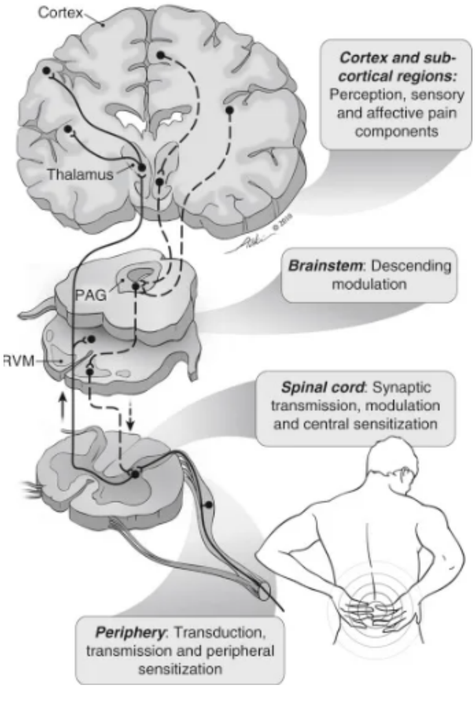

Figure 3. Pain

Pain, whether acute or chronic, exerts profound effects on muscle activity. Acute pain can trigger reflex muscle responses, such as involuntary contractions or inhibition of certain muscle groups. Conversely, chronic pain can induce alterations in posture, muscle tone, and motor function. Additionally, pain activates the autonomic nervous system, eliciting physiological responses like increased heart rate, peripheral vasoconstriction, and the release of stress hormones such as adrenaline and noradrenaline. These autonomic changes impact cardiac activity, which can be detected through ECG recordings. Furthermore, pain induces alterations in electromyography (EMG) signals, reflecting changes in muscle activity. These changes may include involuntary muscle contractions, heightened muscle tone, or shifts in muscle activation patterns, representing the neuromuscular system's response to pain stimuli. Moreover, pain exerts direct and indirect effects on cardiac activity. Activation of the sympathetic nervous system in response to pain can elevate heart rate and contractility, while chronic pain may lead to maladaptive autonomic responses contributing to cardiovascular dysfunction. However, the presence of pain complicates the interpretation of EMG and ECG signals. Both muscular and cardiac responses may be influenced by perceived pain, necessitating consideration of the clinical context and the patient's emotional state when analyzing physiological signals in pain-related scenarios.[25]

E. Ascending pathways

When discussing the ascending pathways of the Central Nervous System (CNS) responsible for transmitting superficial and deep sensitivity, we delve into a fundamental aspect of how the body perceives and reacts to environmental stimuli. These sensory pathways play a critical role in relaying information from peripheral sensory receptors to the brain's sensory areas, thereby impacting both muscular and cardiac responses, as well as the interpretation of signals recorded by electromyography (EMG) and electrocardiography (ECG).

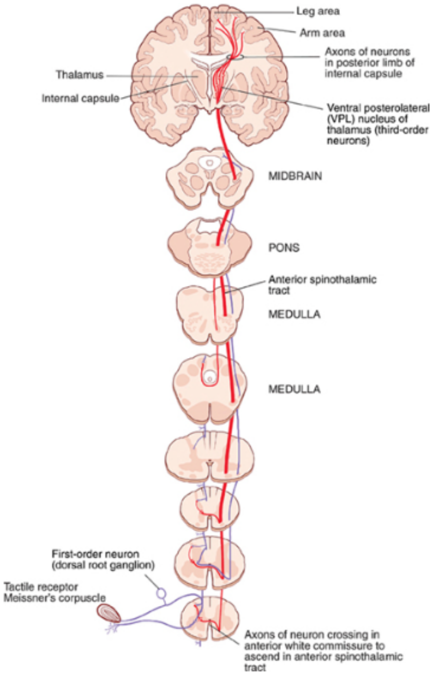

Figure 4. Ascending Pathways

Superficial and Deep Sensitivity: The ascending pathways of the CNS serve as conduits for sensory information originating from receptors in the skin, muscles, joints, and connective tissues, transmitting it to the brain. Superficial sensitivity encompasses tactile, thermal, and nociceptive input from the skin and superficial tissues, whereas deep sensitivity includes proprioceptive feedback from muscles, tendons, and joints.[26]

- Influence on Muscular Response: Sensory signals carried through these ascending pathways play a pivotal role in modulating muscular activity. Proprioceptive and tactile inputs from muscle and cutaneous receptors provide the nervous system with crucial information regarding muscle position, movement, and status, thereby influencing muscular activation and motor coordination.
- Impact on Cardiac Response: Beyond modulating muscular responses, sensory ascending pathways also exert influence over cardiac activity. Visceral sensitivity conveyed through these pathways informs the central nervous system about the internal organ state, including the heart. Consequently, these signals can influence autonomic regulation of heart rate, contractility, and vascular function.
- Interpretation of EMG and ECG Signals: Variations in sensory ascending pathways can have implications for the interpretation of EMG and ECG signals. For instance, changes in tactile or proprioceptive sensitivity may alter muscle activation patterns recorded by EMG, while shifts in visceral sensitivity can affect autonomic responses and cardiac activity detected by ECG.

F. Cellular transport mechanisms

Cellular transport mechanisms are essential processes for ensuring the proper functioning of cells, enabling the movement of ions, molecules, and various substances across cellular membranes. These mechanisms encompass passive transport, including simple and facilitated diffusion, as well as active transport, which necessitates energy in the form of ATP.

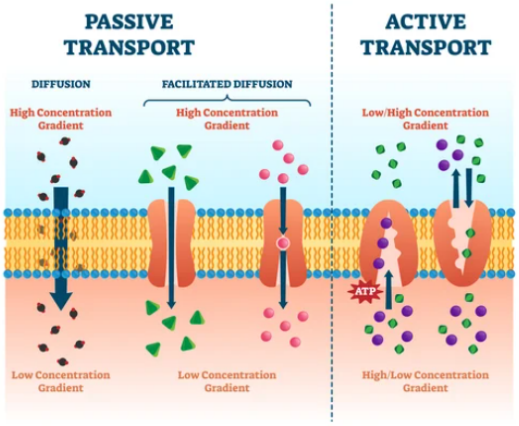

Figure 5. Active and passive cellular transport

- Passive Transport: Simple and facilitated diffusion represent passive transport mechanisms facilitating the movement of molecules along their concentration gradient, from regions of higher concentration to those of lower concentration. While simple diffusion involves molecules passing directly through the cell membrane, facilitated diffusion relies on transporter proteins for assistance.
- Active Transport: Active transport harnesses ATP energy to transport molecules against their concentration gradient, thereby maintaining specific concentration gradients crucial for cellular homeostasis. This transport can be primary, directly utilizing energy for molecular transport, or secondary, utilizing energy derived from the electrochemical gradient of another solute.

The integral membrane proteins known as ion channels form selective pores enabling ions to traverse based on their electrochemical gradient. Conversely, ion pumps, like the sodium-potassium pump, utilize energy to transport ions against their concentration gradient, preserving ionic equilibrium and membrane potential. Ionic balance is pivotal for cellular excitability, particularly in muscle and cardiac cells, where fluctuations in ion concentrations such as sodium, potassium, and calcium are indispensable for generating and propagating electrical signals.

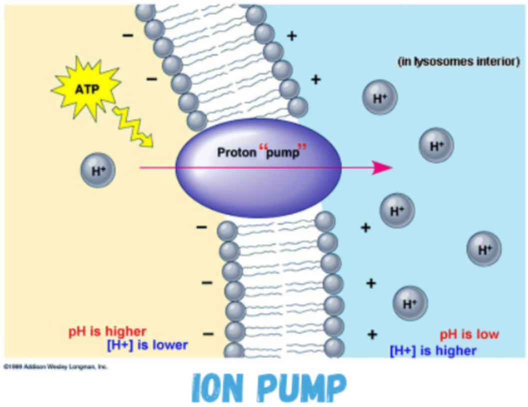

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Figure 6. ION Pump

Disruptions in cellular transport mechanisms can disturb this balance and impact cellular excitability, thereby modifying the excitability and electrical response of muscle and cardiac cells, and subsequently influencing signals detected by electromyography (EMG) and electrocardiography (ECG). For instance, alterations in ionic balance may affect the amplitude and duration of muscle and cardiac action potentials recorded by these techniques.

G. Protein synthesis

Protein synthesis is a fundamental process in all cells, involving the transcription of genetic information from DNA to mRNA, followed by translation into functional proteins. These proteins are essential for various cellular functions, including maintenance, repair, and response to external stimuli, such as electrical signals that can impact signals detected by electromyography (EMG) and electrocardiography (ECG).

During protein synthesis, DNA is transcribed into mRNA, which carries the genetic code to ribosomes for translation into proteins. This process ensures the accurate assembly of amino acids into specific protein sequences according to the genetic instructions encoded in the DNA.

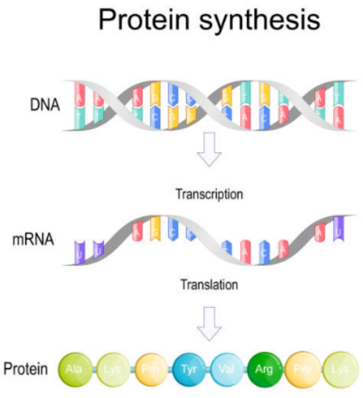

Figure 7. Protein synthesis

Protein synthesis is tightly regulated by a variety of factors, including hormones, growth factors, nutrients, and environmental conditions. These factors can influence the activity of genes and proteins involved in the synthesis process, ensuring that protein production is tailored to the cell's needs.

The proteins synthesized by cells play diverse roles in cellular structure, metabolism, signaling, and muscle contraction. In muscle and cardiac cells, these proteins are particularly important for generating and transmitting electrical signals that regulate muscle activity and cardiac function.

Any disruptions in protein synthesis can affect the ability of muscle and cardiac cells to respond to electrical stimuli. For example, deficiencies in contractile protein synthesis in muscle cells can lead to weakened muscle contractions, affecting the signals recorded by EMG. Similarly, alterations in proteins involved in cardiac excitability can influence the electrical activity detected by ECG.

Membrane potential refers to the difference in electrical charge across the cell membrane, which is essential for cellular excitability. Changes in membrane potential, such as those occurring during action potentials, play a critical role in transmitting electrical signals within cells and between cells in muscle and nerve tissues.

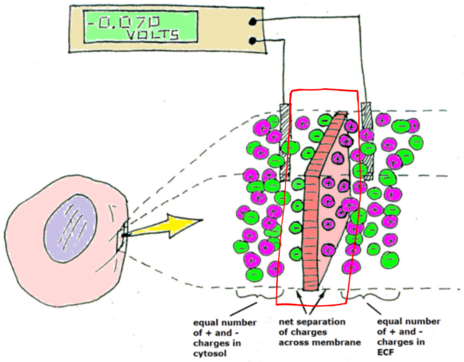

Figure 8. Membran Potential

In muscle and nerve cells, changes in membrane potential are vital for generating and transmitting electrical signals that trigger muscle contractions and nerve impulses. These processes are crucial for the proper functioning of the neuromuscular and cardiovascular systems.

Variations in membrane potential and action potential can directly influence the quality and amplitude of signals recorded by EMG and ECG. Changes in the excitability of muscle cells can alter the characteristics of EMG signals, while variations in cardiac electrical activity can affect the patterns observed in ECG recordings.

H. Circuit Design

When designing circuits for ECG-EMG signal conditioning, several factors need to be considered to ensure optimal performance and reliable signal acquisition:

- Noise Reduction: ECG and EMG signals are often very low amplitude and can be easily corrupted by noise from various sources such as power lines, electromagnetic interference, and movement artifacts. Therefore, it's crucial to include filtering stages in the circuit to reduce noise and interference.

- Signal Amplification: The ECG and EMG signals typically have low voltage amplitudes and need to be amplified for proper detection and analysis. Amplification stages, such as instrumentation amplifiers (e.g., INA), are used to increase the signal amplitude while maintaining high input impedance and low noise.
- Frequency Response: ECG and EMG signals contain important information across a wide range of frequencies. Therefore, the circuit should have a frequency response tailored to capture the relevant physiological information while filtering out unwanted noise and interference. This often involves the use of bandpass filters to selectively pass frequencies of interest.
- Baseline Wander Removal: Baseline wander refers to slow variations in the signal caused by changes in electrode-skin impedance or movement artifacts. Techniques such as high-pass filtering are employed to remove baseline wander and isolate the desired signal components.
- Common Mode Rejection: ECG and EMG signals are often measured differentially to reject common-mode noise originating from sources external to the body. Differential amplifiers, such as instrumentation amplifiers, provide high common-mode rejection ratios to minimize interference from common-mode noise.
- Patient Safety: Safety considerations are paramount when designing medical devices. This includes ensuring that the circuit meets electrical safety standards, such as isolation from mains voltage, proper grounding, and protection against electric shock hazards.

Regarding specific components:

- Notch Filter: A notch filter is used to attenuate specific frequencies, such as power line interference (e.g., 50 or 60 Hz), while preserving the rest of the signal. This helps to remove unwanted noise without affecting the signal of interest.
- INA (Instrumentation Amplifier): An INA is commonly used in ECG-EMG signal conditioning circuits due to its high input impedance, low noise, and high common-mode rejection ratio. It provides accurate amplification of the differential input signal while rejecting common-mode noise.

V. RESULTS

Understanding these principles and selecting appropriate components and circuit configurations are essential for designing effective ECG-EMG signal conditioning circuits that provide reliable and accurate signal acquisition for clinical or research purposes. The circuit designed for ECG-EMG signal conditioning consists on several stages that allow precise and adjustable capture of biological signals. In the first stage, the signal from two channels along with a common reference is amplified by an instrumentation amplifier INA128. This component provides high-precision amplification with low distortion, suitable for biomedical applications.

After initial amplification, the signal passes through an RC low-pass filter, implemented using resistance and capacitance components, and is followed by a TL072 operational amplifier configured as a variable gain amplifier. This amplifier allows adjusting the signal gain to suit the individual characteristics of each patient, using a potentiometer (trimmer) connected to one of its feedback terminals.

Once the gain is adjusted, the signal undergoes a NOTCH filter to remove the 60Hz electrical network frequency and its harmonics. This filter, again implemented with passive components, helps eliminate unwanted line artifacts that could affect signal quality.

Subsequently, the filtered signal passes through a high-pass filter to remove low-frequency components, such as DC drift, ensuring that the signal is centered around zero volts to facilitate further processing.

To adapt the signal to the individual characteristics of each patient, a zero-span circuit is employed to generate a variable DC signal. This DC signal is adjusted using another potentiometer connected to a circuit powered with 5V, allowing the elevation or decrease of the signal level as needed.

Finally, to ensure that the resulting signal is completely positive, a zener diode is used connected to an integrated circuit that provides -5V for the supply of the operational amplifiers. This ensures that any negative component of the signal is clipped, thus simplifying subsequent processing and analysis. Below is the schematic for the designed circuit with two channels:

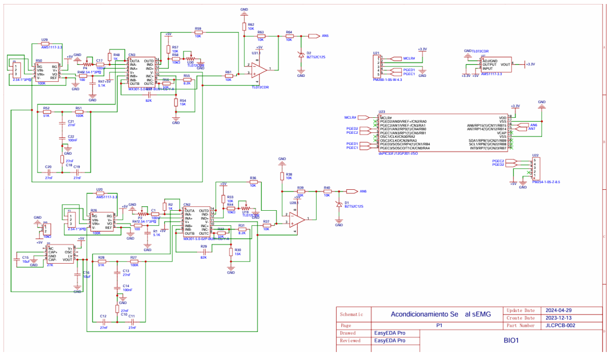

Figure 9. schematic

Here is the PCB design for the ECG-EMG signal conditioning circuit.

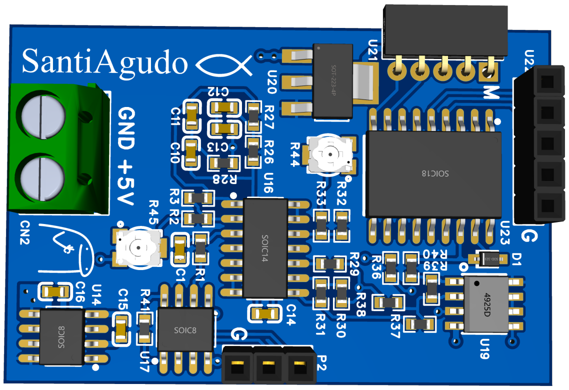

Figure 10. PCB

This PCB design takes into account the arrangement of electronic components, cable connections, and space optimization to ensure a compact and functional circuit. Components are strategically placed to minimize interference and facilitate assembly and soldering.

Copper traces of varying widths are used to handle currents and voltages appropriately, avoiding interference and signal losses. Additionally, mounting holes are included to securely fasten the PCB to a housing or structure.

The PCB design has been optimized to ensure reliable and consistent performance of the ECG-EMG signal conditioning circuit, facilitating its integration into larger systems or medical devices. The circuit was tested with the assistance of a healthy 24-year-old patient, to whom three electrodes were attached to the chest to observe their ECG signal using an oscilloscope.

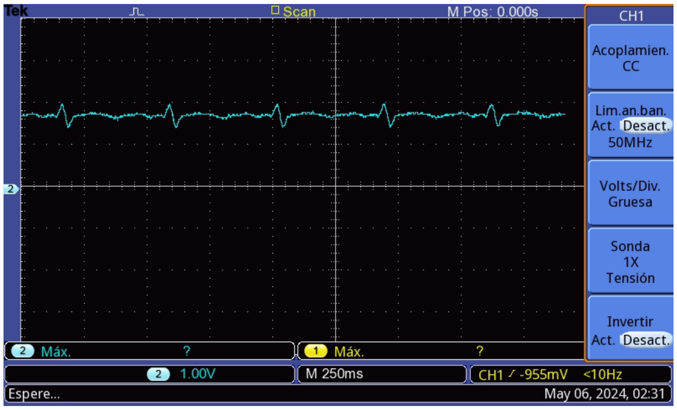

Figure 11. ECG

As seen in Figure 11, we have a fairly clean ECG signal ready to be processed, meeting the maximum voltage range for input to a microprocessor. On the other hand, in Figure 12, the signal gain was adjusted, increasing it and thus generating greater noise interference. However, this does not significantly affect signal processing.

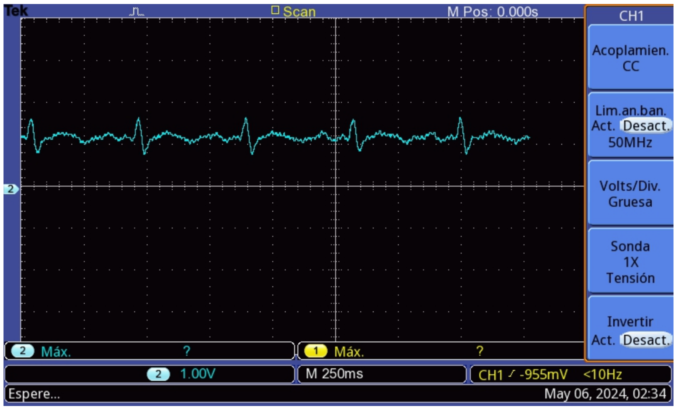

Figure 12. Gain adjustment

Finally, the signal period was adjusted so that the oscilloscope could calculate the maximum voltage of the signal, which was found to be 2.16V. This is favorable since the maximum allowable voltage is 3.3V.

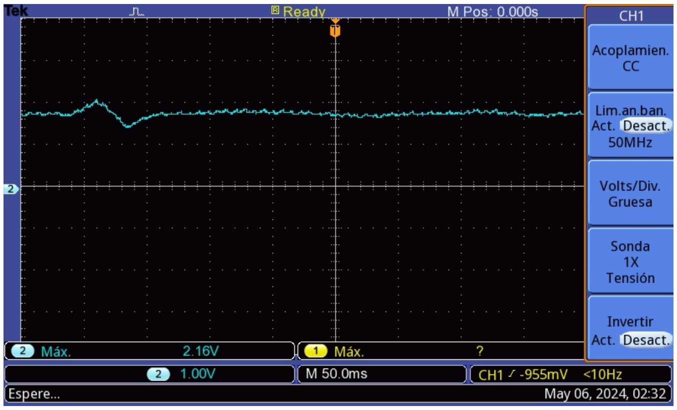

Figure 13. Signal voltage

VI. CONCLUSIONES

- The combination of knowledge in morphophysiology with electronic design techniques has allowed the development of a signal conditioning circuit for electromyography (EMG) and electrocardiography (ECG) that adapts to the morphophysiological variations of patients. This is reflected in the circuit's ability to capture clear and precise signals, as observed in the test conducted with a 24-year-old patient.
- Adjusting the circuit gain showed that while increased gain can introduce more noise interference, it does not significantly affect signal processing, demonstrating the circuit's robustness in maintaining signal quality even at higher gains.
- The circuit's robustness and precision make it suitable for clinical and research applications in medicine and biomechanics. It reliably and accurately captures EMG and ECG signals, opening new possibilities for monitoring and diagnosing neuromuscular and cardiovascular disorders, as well as assessing biomechanical function.
- The developed signal conditioning circuit also has significant implications for assistive technologies, such as

EMG-controlled prosthetics and wearable cardiac monitoring systems. By integrating morphophysiology with electronics, new opportunities arise to improve the quality of life for people with disabilities and medical conditions.

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