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Dedicatoria

“Dedico este trabajo a mi mamita y a mi papi quienes son los pilares fundamentales de mi vida, y que siempre han estado para apoyarme sin importar la dificultad, tanto en ideas locas como a lo largo de toda mi carrera. A mi ñañita por siempre estarme motivando a continuar y buscar la forma de sacarme una sonrisa. A mis abuelitos Paquita, Marco, Teresita, y Luis por su amor incondicional y apoyo constante en esta etapa. En general, a toda mi familia y amigos que siempre estuvieron acompañándome en este sueño que ahora es una realidad.”

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Bryan Bolívar Cerón Andrade

Resumen

Las prótesis de miembros superiores en Ecuador son muy limitadas, aunque no excepcionalmente funcionales, y sus costos son elevados. Por esta razón, el sistema de salud se limita al uso de ganchos o manos estéticas no funcionales debido a su bajo costo de adquisición. Para proponer una solución a los problemas planteados, es fundamental considerar la fisiología del brazo, los tipos de amputaciones, la señal mioeléctrica generada por la contracción muscular, y los tipos de prótesis que existen actualmente. Así, se diseñó un electromiógrafo para detectar la señal EMG y una prótesis mioeléctrica transhumeral funcional del miembro superior a bajo costo. Una potencia mioeléctrica externa controla este tipo de prótesis. En otras palabras, el sensor mioeléctrico conectado por electrodos al brazo de la persona (muñón) detecta la contracción y flexión muscular, generando una señal eléctrica. He fabricado el circuito del sensor mioeléctrico con componentes electrónicos que están fácilmente disponibles en el país. La prótesis se imprimió en 3D con filamento PLA. Los movimientos que puede realizar no son los mismos que los de una mano normal, pero sirve a uno de los movimientos más importantes dentro de las actividades diarias, tomar y soltar objetos, cerrar y abrir la mano. De esta forma, la mano protésica tiene 6 grados de libertad, uno para cada dedo y otro para la muñeca. Por lo tanto, se espera que brinde una ayuda leve y mejore la calidad de vida de las personas que tienen amputaciones o malformaciones en las extremidades superiores.

Palabras clave: Extremidades superiores, amputaciones, señal mioeléctrica, electromiógrafo, mano, prótesis.

Abstract

Upper limb prosthesis in Ecuador are very limited, albeit not exceptionally functional, and their costs are high. For this reason, the health system is limited to the use of non-functional aesthetic hooks or hands due to its low acquisition cost. To propose a solution to the problems raised, it is essential to consider the physiology of the arm, the types of amputations, the myoelectric signal (EMG) generated by muscle contraction, and prosthesis that currently exist. Thus, an electromyograph was designed to detect the EMG signal and functional upper limb transhumeral myoelectric prosthesis at low-cost. An external myoelectric power controls this type of prosthesis. In other words, the myoelectric sensor connected by electrodes to the person's arm (stump) detects muscle contraction and flexion, generating an electrical signal. I manufactured the myoelectric sensor circuit with electronic components that are readily available in the country. The prosthesis was 3D printed with PLA filament. The movements that it can perform are not the same as those of a normal hand, but it serves one of the most important movements within daily activities, taking and releasing objects, closing and opening the hand. In this way, the prosthetic hand has 6 degrees of freedom, one for each finger and one for the wrist. Thus, it is expected to provide mild help and improve people's quality of life who have amputations or upper limb malformations.

Keywords: Upper extremities, amputations, myoelectric signal, electromyograph, hand, prosthesis.

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Chapter 1

Introduction

1.1 Problem Statement

World Health Organization (WHO) predicts that 650 million people in the world have some disability. Among the main reasons people with amputated limbs are unexploded landmines, war, work, car accidents, diabetes, and polio diseases. 80% of these people live in underdeveloped countries. According to WHO, less than 5% of people have access to rehabilitation services to improve their lifestyles [27]. According to Instituto Nacional de Estadística y Geografía (National Institute of Statistics and Geography), in Mexico in 2010, there were 664 thousand people who lost some of their limbs, and 35% of these correspond to the amputation of one of the hands [5].

According to Consejo Nacional para la Igualdad de Discapacidades (National Council for the Equality of Disabilities), there are currently more than 475 thousand people registered with disabilities in Ecuador, and 46.65% of these people have physical disabilities [49]. However, there are no accurate data on different physical disabilities in the country. Around 15 thousand people in need of a new or replacement prosthesis in Ecuador [50]. The medical system in underdeveloped countries does not include in its health regulations the problem of amputations and the adaptation of a robotic prosthesis [5].

The biggest problem lies in the amputations of upper limbs since there is very little research in this area and, therefore, the costs of these prosthesis are incredibly high. The health system is limited to non-functional aesthetic hooks or hands due to its low acquisition cost, but this technology is obsolete in the 21 century. Thus, this work focuses on developing an electromyograph to detect the EMG signal, and of a myoelectric prosthesis of 6 degrees of freedom controlled through this signal.

1.2 Thesis Overview

This work is organized as follows: chapter 3 has essential concepts related to the physiology of the human arm, the types of amputations and prosthesis, and a description of the origin of the myoelectric signal. The chapter also has definitions and electronic components necessary to understand the electromyograph's construction and the prosthesis. This chapter ends with a description of 3D printing and a comparison of the main filaments used.

Chapter 4 contains a detailed explanation of the methodology, including the electromyograph circuit's design, acquisition, amplification, filtering, and control of the myoelectric signal.

Chapter 5 contains the results and detailed discussion of the myoelectric signal obtained in each phase. Also shown is a comparison of the designed electromyogram with the MyoWare sensor. Later, this chapter includes a biomechanical analysis and evidence of the printed prosthesis. Finally, the chapter shows a cost analysis of the entire project.

This work ends with chapters 6 and 7, which contain the main problems faced during the preparation of the project, conclusions, and future perspectives on myoelectric prosthesis's construction and development.

Chapter 2

Objectives

2.1 General Objective

- To develop a prosthesis driven by upper limb muscles in transhumeral amputations to allow the patients to grab objects.

2.2 Specific Objectives

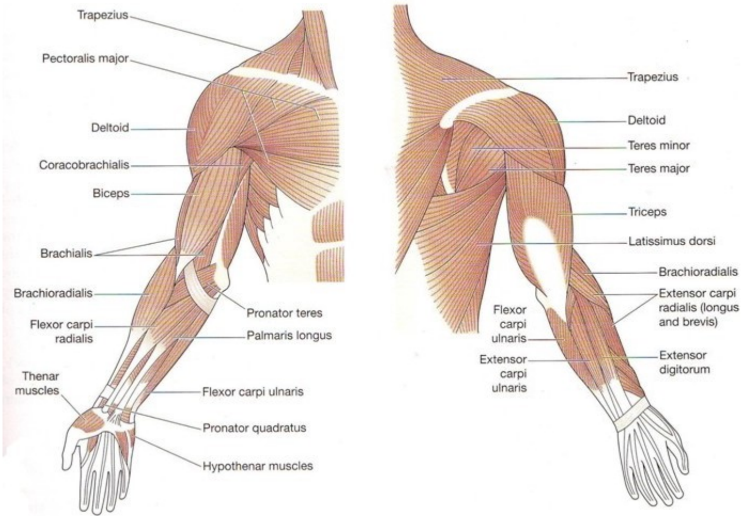
- To develop an electromyograph of low cost to detect the EMG signal.
- To develop a myoelectric prosthesis of 6 degrees of freedom controlled through the patterns of the detected signal.
- To review a better Open Source design for human limb myoelectric prosthesis.
- To implement a myoelectric prosthesis in a 3D printer as a low cost.

Chapter 3

State of the Art

3.1 Upper Limb Physiology

The upper extremities are formed of neurovascular, lymphatic, muscle, and bone tissues. The union and joint work of all these components allow us to carry out daily activities [1]. It is essential to consider the anatomical structure and muscles of the shoulder, arm, elbow, hand, forearm, and wrist (Figure 3.1).



(a) (b)

Figure 3.1: Main muscles of the upper limb [2]: (a) front view of human body, (b) back view of human body.

The shoulder is mainly composed of the clavicle and scapula that articulate with the proximal humerus. The intrinsic muscles of support are the deltoid, teres major, teres minor, trapezius, pectoralis major, coracobrachialis, and latissimus dorsi [1].

The upper arm is the part that goes from the shoulder to the elbow. The humerus is the only bone providing structure. Major muscles controlling movement include biceps, triceps, and brachialis [3].

The elbow is a synovial hinge joint between the humerus, radius, and ulna. These joints are the ulno-humeral, radio-humeral, and radio-ulnar. Innervation at the elbow level includes several nerves, such as the musculocutaneous nerve that innervates the brachial biceps. The radial nerve innervates five muscles: the lateral brachial, anconeus, supinator, brachioradialis, brachial triceps. The ulnar nerve and median nerve innervate the muscles of the forearm and hand [1].

The forearm is composed of two main muscle groups: intrinsic and extrinsic. The intrinsic muscles are responsible for pronouncing and suppressing the radius and ulna to produce 180-degree movement. The extrinsic muscles are responsible for flexing and extending the fingers. The forearm has about 20 muscles, divided into the anterior flexor compartments and posterior flexor compartments. The main nerves are median, ulnar, and radial [1].

The wrist is made up of two rows of proximal and distal carpal bones. The four proximal bones are scaphoid, semilunar, triquetrum, and pisiform, and they are articulated with radius and ulna for wrist movement. The four distal bones are trapezium, trapezoid, capitate, and hamate [1].

The human hand is of vital importance due to its structure and function [4]. The hand is composed of 27 bones divided into three groups: 8 carpals, 5 metacarpals, and 14 phalanges. Movement is controlled by 31 muscles, giving a hand 25 degrees of freedom [5].

The main movements of the upper limb are (Figure 3.2):

1. **Arm flexion/extension:** The arm's flexion is the forward movement, and the muscles involved are pectoralis major, coracobrachialis, biceps brachii, and the an-

terior fibers of the deltoid. The arm's extension is the backward movement, whose muscles involved are latissimus dorsi and teres major, long head of triceps, posterior fibers of the deltoid [6].

2. **Arm adduction/abduction:** Arm adduction is movement from the initial position of the arm towards the midline of the body in the coronal plane around 40° using the pectoralis major, latissimus dorsi, and teres major and minor [7]. Abduction of the arm is the opposite movement to that of adduction; that is, moving away from the midline of the body in the coronal plane using the deltoid (middle fibers) and supraspinatus [8].

3. **Arm medial/lateral rotation:** The arm's medial rotation is performed with the elbow flexed and turning the hand toward the midline. The muscles that perform this movement are the subscapularis, latissimus dorsi, teres major, pectoralis major, and the deltoid's anterior fibers. The arm's lateral rotatory movement is conducted with the elbow flexed, and the rotating hand is moving away from the midline. The muscles involved are the infraspinatus and teres minor, posterior fibers of the deltoid [6].

4. **Elbow flexion/extension:** Elbow flexion is the hand's movement approaching the shoulder by way of the biceps brachii, brachialis, and brachioradialis. Elbow extension occurs in the opposite direction; that is, the hand moves away from the shoulder through the triceps brachii and anconeus [6].

5. **Forearm pronation/supination:** These are unique movements for the body and in conjunction with the hand. The pronation movement is the palm facing down using the pronator teres, pronator quadratus, and brachioradialis. The supination movement is palm up with the use of supinator and biceps brachii [9].

6. **Wrist flexion/extension:** Wrist flexion is the joint movement of the whole hand approaching the forearm with the flexor carpi radialis and flexor carpi ulnaris. The extension of the wrist is the joint movement of the entire hand away from the

forearm. The muscles exerted this movement are extensor carpi radialis longus and brevis, and extensor carpi ulnaris [6].

7. **Wrist adduction/abduction:** Wrist abduction is the hand's movement laterally towards the radius with the flexor carpi radialis, and extensor carpi radialis longus and brevis. The wrist's adduction is the movement in the opposite direction towards the ulnar using the flexor and extensor carpi ulnaris [6].

8. **Finger flexion/extension:** It is the movement to grasp objects. The fingers' flexion is the movement of the fingers towards the palm through the interossei and lumbricals, flexor digitorum superficialis, and flexor digitorum profundus. The fingers' extension is in the opposite direction of flexion using the interossei and lumbricals, and extensor digitorum (communis). Also, independent muscles are used for each finger [6].

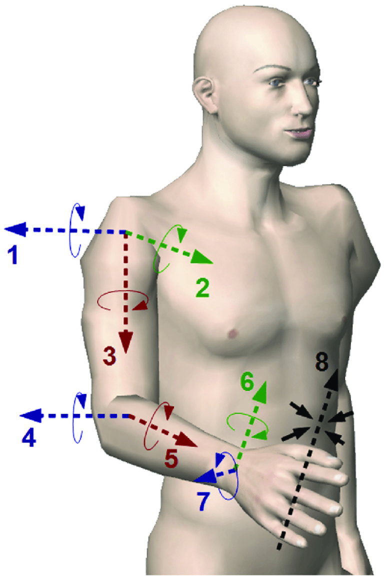


Figure 3.2: Main movements of the upper limb. Numbers: 1: arm flexion/extension, 2: arm adduction/abduction, 3: arm medial/lateral rotation, 4: elbow flexion/extension, 5: forearm pronation/supination, 6: wrist flexion/extension, 7: wrist adduction/abduction, 8: finger flexion/extension [10]. Colors: blue: backward motion, red: rotation on the axis itself, green: forward motion, black: clamp movement.

3.2 Myoelectric Signal

The myoelectric signal (EMG) results from the excitability of muscle fibers due to muscle contraction. In other words, the EMG signal measures the electrical currents generated by the muscles during contraction and represents neuromuscular activities. This activity depends on the anatomical and physiological properties of the muscles [11]. It is essential to understand the characteristics of the EMG signal to be applied in the prosthetic area. Some characteristics are a bandwidth of 10 to 300Hz with an optimum point around 100 Hz [12], and amplitude varies in a range of μV up to 10 mV [13].

Essential functions such as heartbeat, breathing, thinking are performed in the human body through electrical impulses that generate a difference in electrical potential by ionized particles, particularly potassium (K), chlorine (Cl), sodium (Na), calcium (Ca) ions, leading to depolarization of their membranes [14]. Small electrical impulses, known as action potentials, are sent to motor neurons through the nerves. Motor neurons send action potentials to muscles [15], giving rise to motor units (MU). Motor units consist of neurons and muscle fibers they innervate. Innervation of other tissues is not referred to as motor units.

A MU is a set of motor neurons in the spine, axon, and muscle fibers innervated [15]. Thus, the muscle is a set of motor units arranged in parallel and whose activity, known as the Potential Motor Unit (PMU), is the minimum individual element of muscle contraction [16].

3.2.1 Characteristics

The EMG signal is a function of time and described in terms of its amplitude, frequency, and phase [17] (Figure 3.3).

The main parameters of the EMG signal are:

- **Amplitude:** is the voltage difference from the maximum negative peak to the maximum positive peak within the duration of a Potential Motor Unit (PMU), and the number of active muscle fibers of a motor unit within the electrode absorption area is inferred [11].

- **Frequency:** is the time interval between the waveform's first and the last appearance is exceeding a predefined amplitude threshold [11].

- **Phase:** is a section of a PMU between two baseline crossings and reaches an absolute value of amplitude greater than 0.02 mV [11].

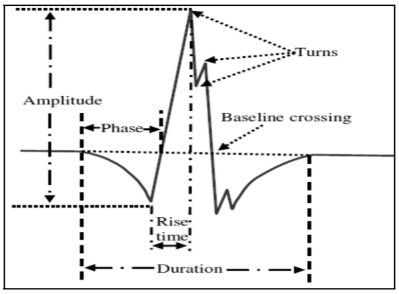


Figure 3.3: Characteristics of the EMG signal [11].

3.3 Acquisition of EMG Signal

In recent years, the importance of electromyography has grown considerably due to its applications and innovations in the field of biomedical engineering [18]. Electromyography is the result of reading the difference in the electric potential of the muscle. Transducers are used to convert a physical unit into an electrical signal, which enters an electronic circuit. The electrodes act as a transducer to detect the electrical signal generated in the muscles without a change in physical magnitude [13].

In the area of electromyography, transducers are known as electrodes. After reading the EMG signal, the electrodes are in charge of transforming it to obtain information from the potential difference [20]. Thus, the electrodes are responsible for converting ionic currents in living tissue into electron currents capable of circulating through metallic conductors [15].

There are two types of electrodes used in electromyography: invasive and non-invasive. Invasive electrodes are placed through surgery inside the muscle. Non-invasive electrodes are placed on the skin's surface using a gel to reduce noise and are classified into monopolar and bipolar. Monopolar performs the EMG signal reading without a reference since they have a significant penetration into the muscle. Bipolar uses two electrodes to obtain the muscle's potential difference, and they perform the reading by adding a reference.

3M Red Dot commercial electrodes are disposable non-invasive monitoring electrodes with gel adherent to the skin (Figure 3.4). They are 4.06 cm x 3.45 cm in size, are made of foam, and the sensor material is silver/silver chloride coated plastic [21].

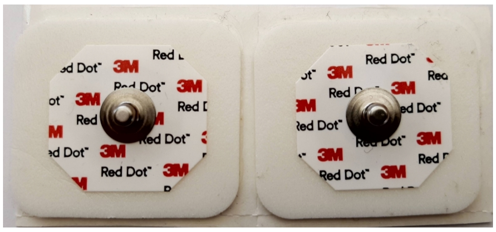


Figure 3.4: 3M Red Dot electrodes.

Figure 3.5 shows the recommended electrode placement points for the most optimal reading of the signal and less noise. SENIAM Project recommends placing the two bipolar reading electrodes at a distance of 20 mm between them. In this way, it should not exceed 1/4 of the length of the muscle fiber to avoid effects on the tendons [23].

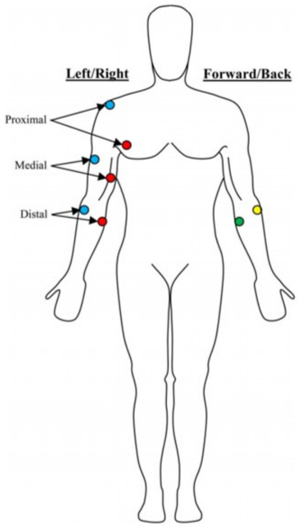
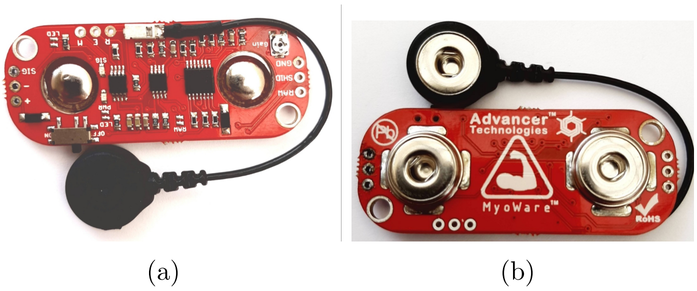


Figure 3.5: Electrode placement locations [22].

The best known commercial devices to detect the EMG signal are:

- **MyoWare sensor (Figure 3.6):** It is currently one of the most used sensors for electromyography due to its characteristics, such as tiny size, voltage supply of 2.9 V to 5.7 V, and adjustable gain. Uses two electrodes for signal acquisition and one electrode for reference, and has two output modes: EMG Envelope and Raw EMG [24]. In Ecuador, it has a cost of $70.



(a) (b)

Figure 3.6: MyoWare sensor: (a) front view, (b) back view.

- **Myo Armband sensor (Figure 3.7):** It is a revolutionary wireless bracelet to read the muscles' electrical activity and arm movements. It has more than 100 applications, and it is compatible with Mac, Windows, iOS, and Android [25]. It uses a 9-axis inertial unit and detects the forearm's movement, orientation, and rotation [26]. Currently, it is no longer for sale.

Figure 3.7: Myo Armband sensor [25].

3.4 Amputations

Upper limb amputations are caused due to innumerable reasons such as work accidents, car accidents, bites, poor post-operative care. The person who loses his limb suffers enormous physical and psychological damage and needs rehabilitation and psychological therapy to help himself. However, as mentioned above, of all amputees, only 5 % have access to rehabilitation services [27]. Upper limb amputations vary from removing a part of the finger to the complete amputation of the arm [28] (Figure 3.8). Table 3.1 shows the main types of amputations.

Table 3.1: Definition of the types of upper limb amputations.

Type	**Definition**
Partial and complete hand amputation	It is the amputation of the part of the fingers until the complete amputation of the hand. The loss of the thumb is the most serious since it prevents grabbing, manipulating, or lifting objects [28].
Wrist disarticulation	The complete amputation of the hand and wrist [28].
Below elbow amputation (Transradial)	It involves a partial amputation of the forearm. It is the removal of the arm under the elbow [28].
Elbow disarticulation	Amputation of the forearm just at the elbow [28].
Above elbow amputation (Transhumeral)	Amputation of the forearm above the elbow [28].
Shoulder disarticulation	The amputation of the whole arm, and of the shoulder blade and clavicle [28].
Interscapulothoracic (Forequarter)	It is the amputation of the entire arm, part of the clavicle, and division of the subclavian vessels [29].

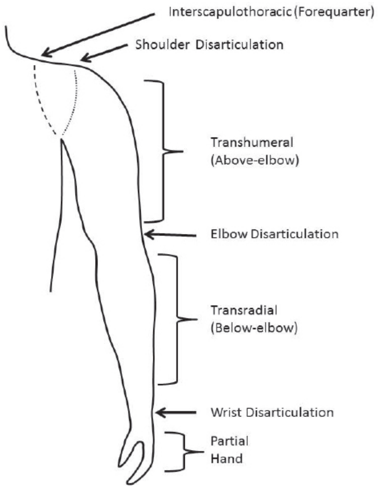


Figure 3.8: Types of upper limb amputations [30].

3.5 Upper Limb Prosthesis

There are four main types of prosthesis for people who have suffered some amputation such as cosmetic, body-powered (mechanical), myoelectric, and hybrid:

- **Cosmetic Prosthesis (Figure 3.9.a)**

  They are used for cosmetic purposes because they have no movement in the parts that make it up. Its aesthetic resemblance is very similar to that of a hand but without any function [31].

- **Body-Powered (mechanical) Prosthesis (Figure 3.9.b)**

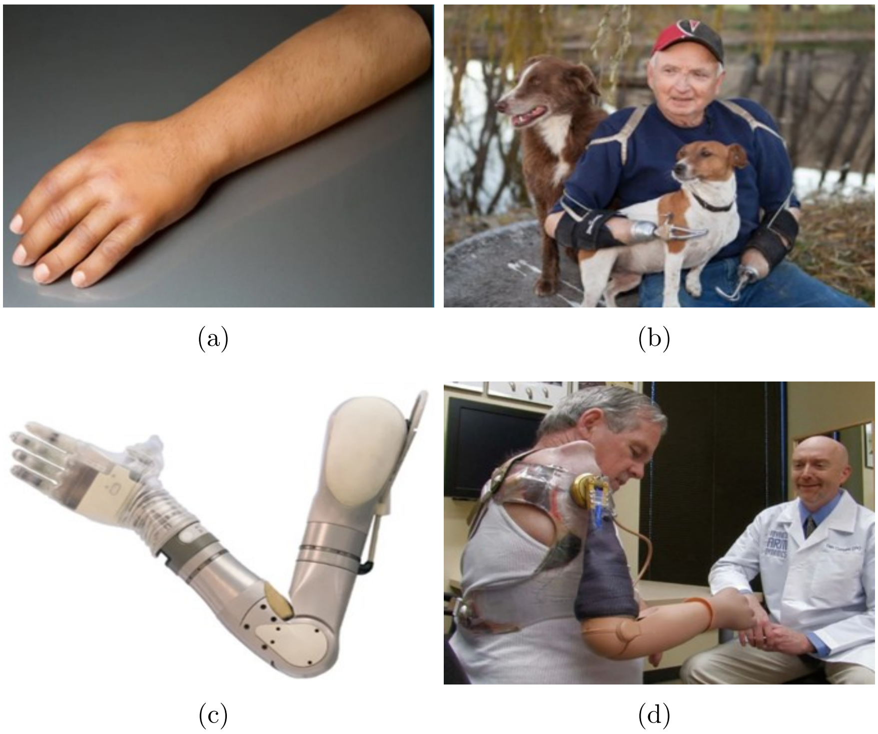
  These prosthesis are the most used and economic ones because they use a control system using cables and bandages to operate. It uses cables attached to the back or its remaining limbs that allow them to make any movement [27].

- **Myoelectric Prosthesis (Figure 3.9.c)**

  Its system is operated through electric motors activated by myoelectric signals generated in muscle movements [57].

- **Hybrid Prosthesis (Figure 3.9.d)**

  This type of prosthesis results in the combination of the operating principles of the mechanical and myoelectric prosthesis; that is, it combines force systems to collect own energy (corporeal) and generate external energy (extracorporeal) [32].


(a) (b)

(c) (d)

Figure 3.9: Types of prosthesis [33]: (a) cosmetic prosthesis, (b) body-powered prosthesis, (c) myoelectric prosthesis, (d) hybrid prosthesis.

3.6 Electronic Fundamentals

It is necessary to define different electronic concepts, to develop the system of this thesis.

3.6.1 Amplification

Amplification or gain refers to the relationship between input and output voltage, input and output current, or input and output power [34] (Figure 3.10). As seen in the following equations:

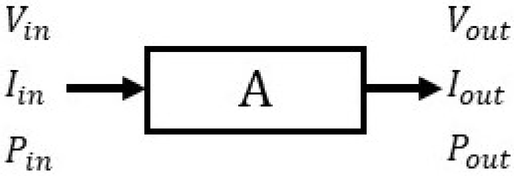


Figure 3.10: Relationship of the amplification (gain).

- **Voltage gain**

$$A_v = \frac{V_{out}}{V_{in}} \tag{3.1}$$

- **Current gain**

$$A_i = \frac{I_{out}}{I_{in}} \tag{3.2}$$

- **Power gain**

$$A_p = \frac{P_{out}}{P_{in}} \tag{3.3}$$

3.6.2 Operational amplifier

The operational amplifier (op-amp) is an electronic device that contains a complex configuration of resistors, transistors, capacitors, and diodes [35]. Commercially it has several presentations (Figure 3.11.a). Figure 3.11.b shows the representative symbol of the operational amplifier.

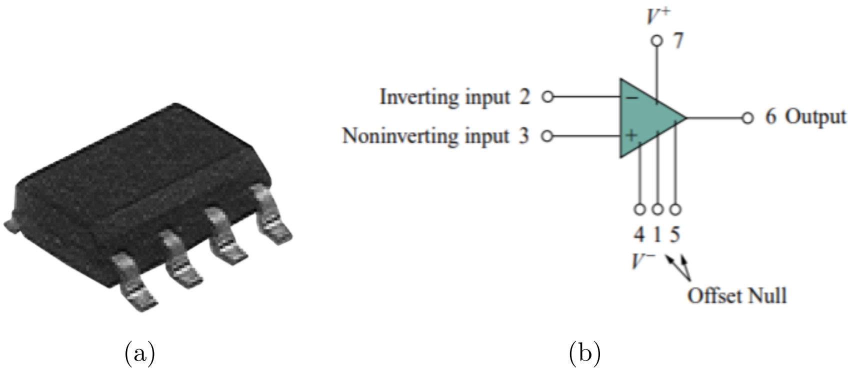


Figure 3.11: Operational amplifier [35]: (a) typical op-amp, (b) op-amp symbol.

In general, op-amps have eight connecting terminals or pins:

- Pin 1: Offset.
- Pin 2: Inverting signal input.
- Pin 3: Non-inverting signal input.
- Pin 4: Negative supply (-V).
- Pin 5: Offset.
- Pin 6: Signal output.
- Pin 7: Positive supply (+V).
- Pin 8: Does not have a defined function.

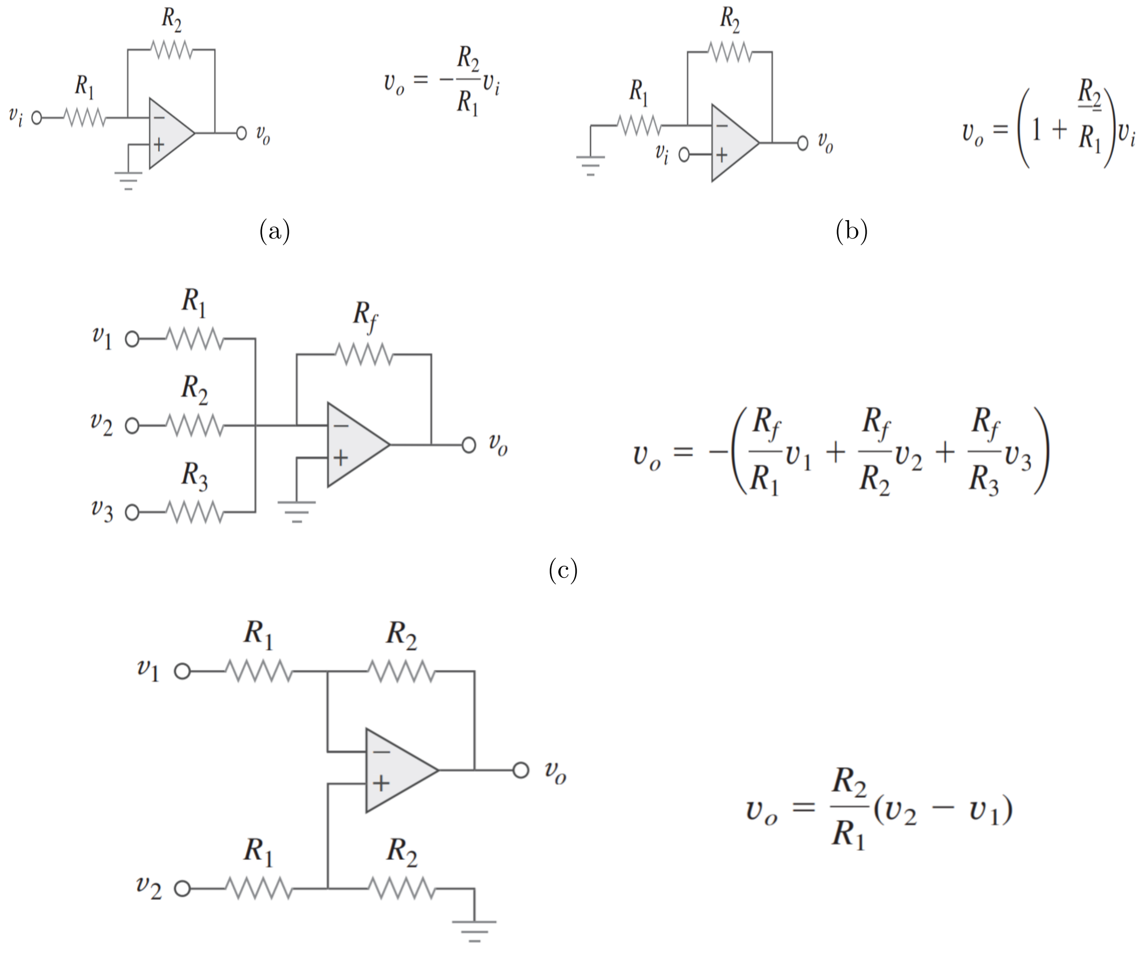
The op-amp is a device designed to perform various mathematical operations according to the configuration of external resistors and capacitors connected to its terminals [35]. Figure 3.12 shows these settings and the relationship between their input and output:

a) **Inverting amplifier:** Its function is to invert the polarity of the input signal and amplify it. Here, pin 3 is connected to ground, pin 2 is connected to the input voltage (Vi) through a resistor (R1), and a feedback resistor (Rf) is connected between pin 2 and pin 7.

b) **Non-inverting Amplifier:** Provides positive voltage gain. Its configuration is pin 3 connected directly to Vi, and R1 connects between pin 2 and ground.

c) **Summing amplifier:** Adds several inputs and produces one output. It uses the inverting amplifier configuration and adds the necessary inputs to pin 2.

d) **Differentiating amplifier:** Its function is to amplify the output signal after obtaining the difference of its two input signals. Its role is very similar to the instrumentation amplifier. An input signal is connected to pin 2, another signal to pin 3 and from this pin, and R2 goes to the ground.



(a)

(b)

(c)

(d)

Figure 3.12: Main configurations of an operational amplifier [35]: (a) inverting, (b) non-inverting, (c) summing, (d) differentiating.

3.6.3 Instrumental amplifier AD620

The AD620 is an instrumental amplifier that uses an external resistance (Rf) to establish gains from 1 to 10000. The following formula is applied to determine the value of gain:

$$G = \frac{49.4k\Omega}{R_f} + 1 \tag{3.4}$$

It has high precision 40 ppm maximum non-linearity, dual power, low noise, low input bias current, and low power ideal for medical applications [36]. It fulfills the function of three operational amplifiers and different configurations of resistances (Figure 3.13). This instrumentation amplifier consists of two functions: amplify (gain) of the two input signals and obtain a difference resulting from the two signals.

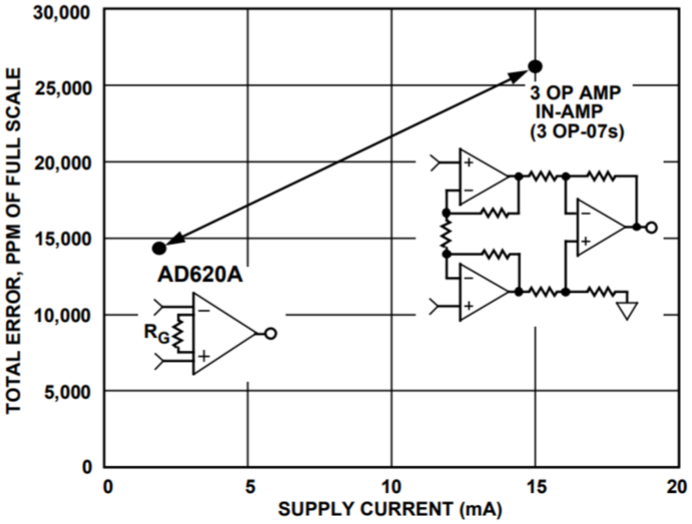


Figure 3.13: AD620 compared to a circuit composed of three op-amps [36].

3.6.4 Filters

Filters are a set of electronic components whose main function is to eliminate specific frequencies of an electrical signal; they can also modify the signal's amplitude and phase [37]. The characteristics of the filters vary depending on the order, and their passive and active configuration. The filter order refers to the maximum delay existing in the elements used in the filter circuit [19]. Passive filters use resistors, capacitors, diodes, and active filters also use operational amplifiers. Among the most used filters are:

a) **Low-pass filter:** This type of filter allows the passage of all the signals whose frequencies are included from a null frequency, up to a cutoff frequency (fc), the other frequencies above this fc will be blocked [32] (Figure 3.14.a). This filter uses an op-amp.

b) **High-pass filter:** This filter allows all signals whose frequencies are above a cutoff frequency (fc) to pass through; that is, all other frequencies between 0 and fc will be blocked [32] (Figure 3.14.b). Uses an op-amp but in different settings to the low-pass filter.

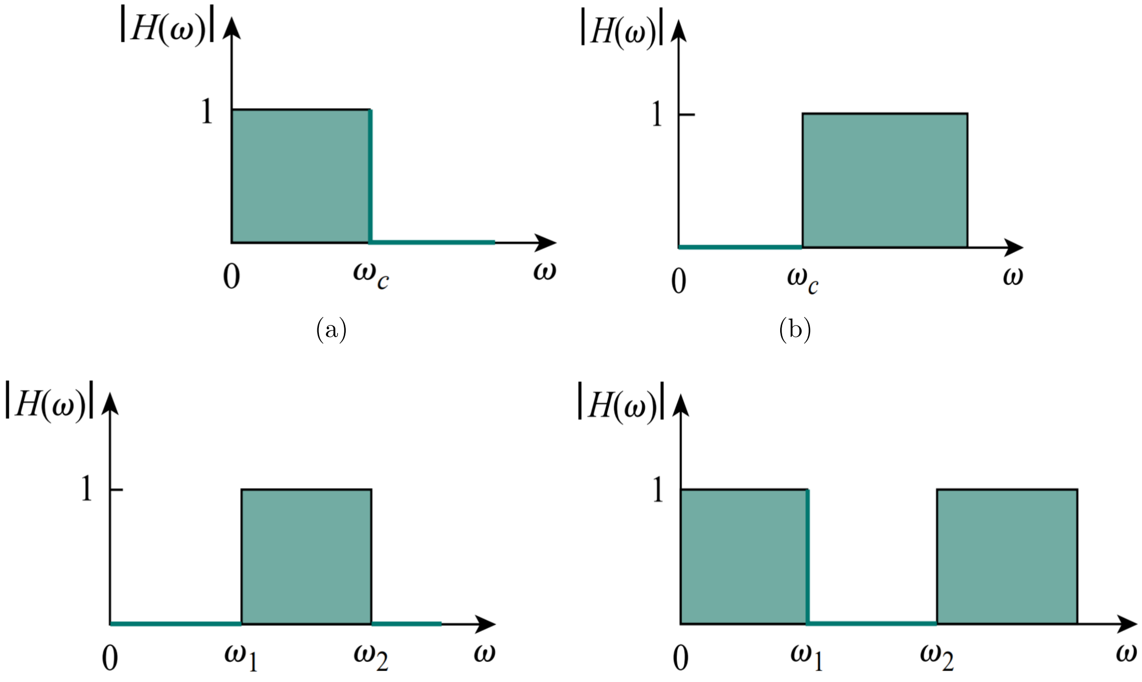
The following equation is used to calculate the cutoff frequency for low-pass filters and high-pass filters:

$$f_c = \frac{1}{2\pi * R * C} \tag{3.5}$$

c) **Band-pass filter:** Allows frequencies within a specific range or band to pass through, frequencies outside this range are attenuated [38]; that is, it is the combination of a low-pass filter and a high-pass filter. This filter uses two op-amps (Figure 3.14.c).

d) **Notch filter:** This filter provides a notch or narrowband over which signals at that frequency are removed (Figure 3.14.d). Two op-amps are used for this filter. The following equation is used to calculate the cutoff frequency in this filter:

$$f_c = \frac{1}{4\pi * R * C} \tag{3.6}$$



(a) (b)

(c) (d)

Figure 3.14: Types of Filters [38]: (a) low-pass filter, (b) high-pass filter, (c) band pass filter, (d) notch filter.

3.6.5 AC/DC conversion

It is the process that transduces or converts analog signals to digital [32], through the use of microprocessors or microcontrollers such as Arduino UNO, Arduino Pro Mini, among others.

- **Arduino UNO board:** It is one of the most used microcontrollers globally due to its characteristics, free access code, and price. It contains an ATmega328P microcontroller. Figure 3.15 shows the features of this board. It has 6 analog inputs, 14 digital input/output pins, a USB connection, a power connector, reset button, among others [39]. Arduino software (IDE) is used to program the board, and data input or output is carried out through the connection with the computer's serial port.

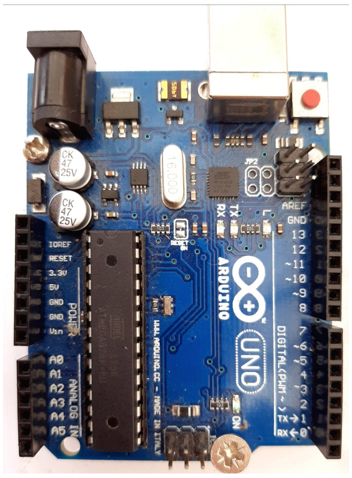


Figure 3.15: Arduino UNO board.

- **Arduino Pro Mini board:** It is one of the smallest Arduino microcontroller boards. It contains an ATmega328 microcontroller. Figure 3.16 shows the following characteristics: 6 analog inputs, 14 input and output pins, an integrated resonator, among others. An FTDI cable or board like Arduino UNO without its microcontroller connects the board to the computer. There are two versions of the Pro Mini: 3.3v and 8MHz, 5v and 16MHz [40].

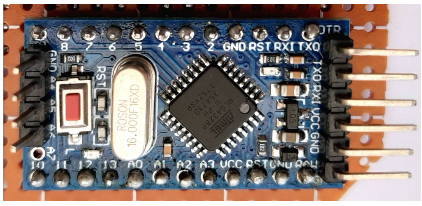


Figure 3.16: Arduino Pro Mini board.

3.6.6 Offset circuit

The offset circuit eliminates the EMG signal's oscillation between very negative or very positive values after the filter stage. In other words, it is a programmable control circuit that provides both positive and negative compensation to carry the input signal in the allowable measurement range of Arduino [41]; that is, in the range of 0 to 5 V.

3.6.7 Servomotors

A servomotor is a structural unit of a servo system with a small motor for drives the load and an encoder for position detection. The servo system can control the position and the speed, depending on the previously established command values [42]. There are several brands and models of servomotors, among the most used, are:

- **SG90 servomotor:** It is a small dimension servomotor with a weight of 9 g (Figure 3.17). It can rotate about 180 degrees, it has plastic gears, and generates a 2.5 kg-cm torque. It has three connection pins: digital output from Arduino, the voltage from 4.8 to 6 V, and ground [43]. The SG90 servomotor has a current consumption of 550mA [62].

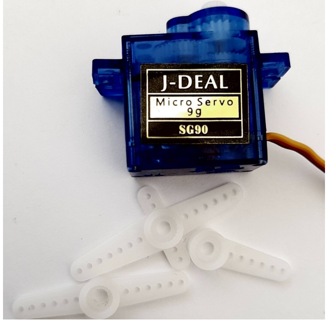


Figure 3.17: SG90 servomotor with its levers [43].

- **MG995 servomotor:** It is a servomotor of larger dimensions than the SG90 and similar connection pins (Figure 3.18). It weighs 55g, metal gears, and 11kg-cm torque. Its supply voltage varies from 4.8 to 6.6 V [44].

Figure 3.18: MG995 servomotor with its levers [44].

3.7 3D Printing

3D printing is a process of additive creation of solid objects by way of melting the filament and placing it in successive layers from a file in digital format [45].

The most delicate parts of the 3D printer need continuous calibration: extruder is where the filament is melted at high temperatures (over 190°) and pushed into the nozzle. The nozzle is a piece with a hole through which the melted filament is pushed out towards the bed. The bed is the printing and fixation base for 3D objects. It must be kept at a specific temperature so as not to alter the printing quality [46].

The order for printing a 3D part is:

1. Obtain an Open Source design or design a 3D model in specialized software such as SolidWorks, AutoCAD, Onshape, among others.
2. Save the model in ".stl" format.
3. Use software such as Ultimaker Cura to slice the model and configure the printing characteristics.
4. Save all these characteristics in ".gcode" format.
5. Perform the calibration of the bed concerning the nozzle of the 3D printer and place the defined filament.
6. Add a fixative so that the base of the 3D piece adheres to the bed of the printer.
7. Print.

There are several types of 3D printers that vary according to their printing characteristics such as printing area, temperature, speed, number of extruders, and kind of material. Depending on the features of the printer, its price varies. One of the currently most used printers is:

- **Creality Ender-3 Pro (Figure 3.19):** It is a 3D fused deposition molding (FDM) printer with a printing area of 22x22x25 cm and a speed of ± 0.1mm per second.

The bed temperature is <110°. The printer can melt and mold various types of filaments, such as PLA, ABS, and TPU [47]. Also, its price is quite affordable compared to other printer models that have similar characteristics.

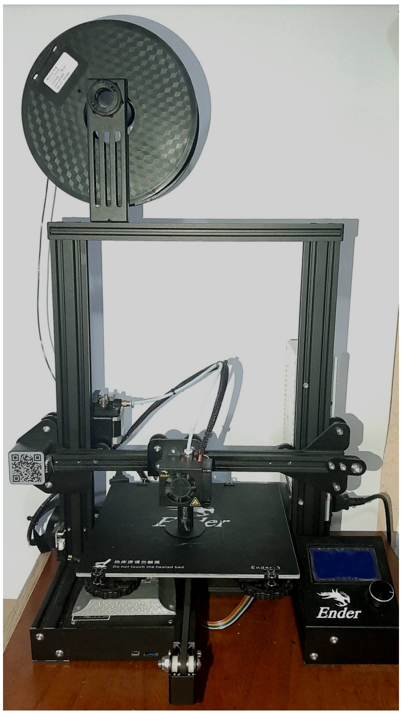


Figure 3.19: Creality Ender-3 Pro 3D printer.

Table 3.2 shows the cost/quality ratio and properties of the currently most commonly used printing materials.

Table 3.2: Properties of the most used filaments [48].

Properties	**PLA**	**ABS**	**TPU**	**PETG**
Strength	High	High	Medium	High
Durability	Medium	High	Very High	High
Flexibility	Low	Medium	Very High	Medium
Print Difficulty	Low	Medium	Low	Low
Print Temperature	180° - 230°C	210° - 250°C	210° - 230°C	220° - 250°C
Shrinkage/Warping	Minimal	Considerable	Minimal	Minimal
Solubility	No	In esters, and ketones	No	No
Cost per kg	$22.00	$25.00	$34.00	$30.00

Chapter 4

Materials and Methodology

The most straightforward prosthesis system includes two parts: a sensor of muscle signal (controlled by the user), and a prosthesis controlled by the sensor signal. The developed project in the present thesis has three parts:

1. Electromyography system,
2. Prosthesis, and
3. A code for controlling the system.

Figure 4.1 shows the system's hardware that includes the circuit of electromyograph and the myoelectric prosthesis, which moves according to EMG's derived signal. The software carries out the processing of EMG signals from the electrical circuit to detect specific patterns and send an execution order to the prosthesis's internal servomotors.

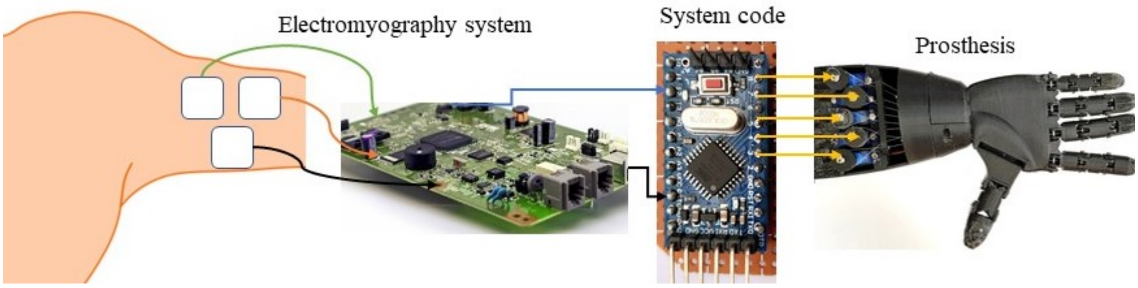


Figure 4.1: General diagram of the project.

Next, each component is explained in terms of its design and implementation.

4.1 Design of Electromyograph Hardware

The EMG signal varies its amplitude in the range from the microvolts to millivolts. Three non-invasive electrodes of 3M Red Dot were used for the register, connected to the biceps (Figure 4.2).

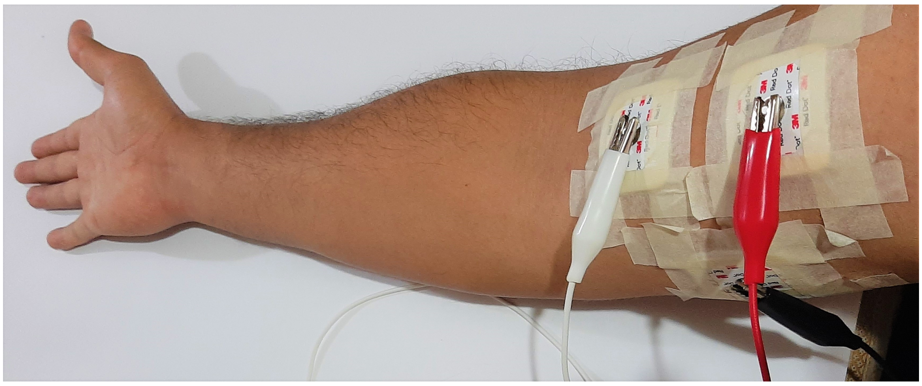


Figure 4.2: 3M Red Dot electrodes connected to the biceps.

An electronic circuit consisting of three phases was developed to achieve signal conditioning, such as acquiring, processing, and treating it (Figure 4.3).

The first phase is the pre-amplification and differentiation of the signal through the instrumentation amplifier.

The second phase consists of signal filtering. The final stage is the offset circuit and the control ground (with the reference electrode), followed by the analogical-digital conversion.

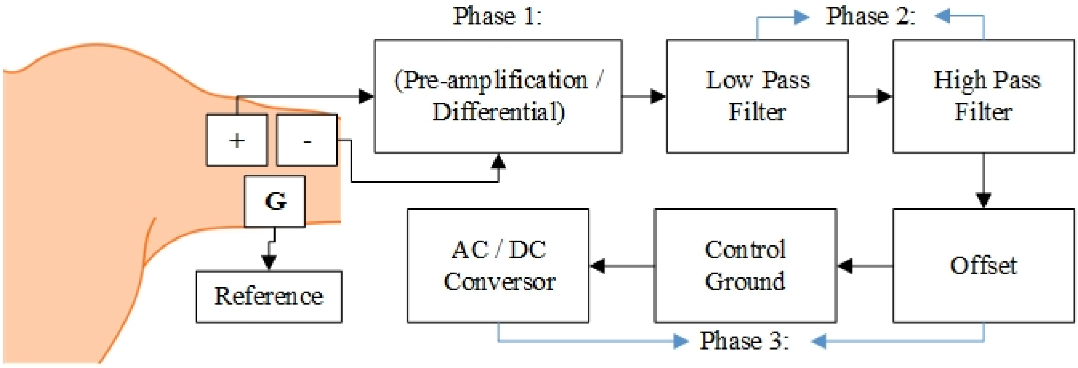


Figure 4.3: Schematic representation of EMG circuit.

4.1.1 Preamplification and differentiation of electrode signals

The signal received from two electrodes (positive and negative) goes to the instrumentation amplifier (AD620). The third electrode is the reference electrode, and it is connected to ground.

In the pre-amplification, the Arduino board can adequately detect the acquired signal's amplitude, requiring a gain of 1000. Therefore, equation 3.4 is used to obtain the resistance value of 49.44 Ω; the closest commercially available value is 50 Ω.

$$R_f = \frac{49.4k\Omega}{G-1} = \frac{49.4k\Omega}{1000-1} = 49.44\Omega \approx 50\Omega \tag{4.1}$$

A differential of the two signal readings of the electrodes is calculated to obtain the differential of the muscle's potential (voltage).

4.1.2 Filtering the EMG signal

In this phase, two filters are used; the main function is to eliminate specific interferences. First, a low-pass filter was used, and then, a high-pass filter, such that they make up a band-pass filter.

A first-order active low-pass filter with a cut-off frequency of 300 Hz and a first-order active high-pass filter with a cut-off frequency of 10 Hz was designed. In this way, a bandwidth of 10 to 300 Hz was obtained. Equation 3.5 was then applied to determine the values for the necessary resistors and capacitors.

- Low-pass filter:

$$R = \frac{1}{2\pi * f_c * C} = \frac{1}{2\pi * 300Hz * (1 * 10^{-6}F)} = 530.52\Omega \tag{4.2}$$

- High-pass filter:

$$R = \frac{1}{2\pi * f_c * C} = \frac{1}{2\pi * 10Hz * (10 * 10^{-6}F)} = 1591.55\Omega \tag{4.3}$$

Initially, I intended to use a notch filter to eliminate the 60 Hz frequency, which can experience interference due to Ecuador's electrical network. However, the device is wireless; that is, the batteries power it, and therefore, the device does not have direct contact with the electrical network.

4.1.3 Control and conversion of the EMG signal

The last phase is subdivided into an offset circuit, mass controller/regulator, and the conversion of the AC/DC signal.

Due to the EMG signal's oscillation between very negative or very positive values, the signal's range exceeds the detectable range of the Arduino board (0 to 5 volts). An offset circuit with a potentiometer was used. The voltage could be regulated so that it is within the detectable range. Finally, the resistance that fulfills the requirement of 330 Ω was obtained.

The next stage, using a mass regulator so that the signal is constant. This regulator directly connects with the reference electrode to control the frequencies eliminated through the filters, which causes certain interferences when sent to ground.

The last sub-phase is converting the analog signal to digital through the Arduino Pro Mini board connected to the computer. The data acquisition frequency is 10 ms, equivalent to the detection of 100 input data in one second.

4.1.4 Final design of the EMG processing circuit

Three alkalines batteries 9 V powered the electromyograph. One battery was connected directly to the Arduino Pro Mini board, and the remaining two batteries were connected to the EMG signal processing circuit. The two batteries are connected in series since the components of this circuit (instrumentation and operational amplifiers) need dual power; that is, positive and negative.

Initially, the circuit assembly was carried out on a protoboard plate for experimentation until the final version was built.

The final circuit was passed to a PCB design (Figure 4.4), to then implement the circuit in a perforated Bakelite, minimizing the interference that long cables can cause. The result was a circuit smaller than of an Arduino UNO board.

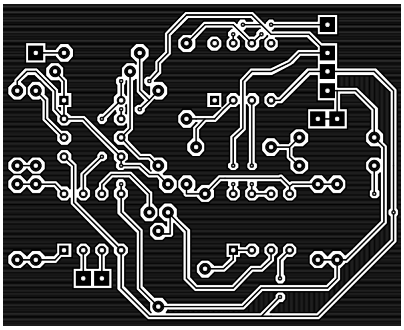


Figure 4.4: PCB layout of the EMG circuit.

4.2 Design of the Myoelectric Prosthesis

4.2.1 Open Source models review

For the design of the prosthesis, an Open Source by Elsayed, M. was used, which was considered a better choice after a bibliographic review and comparisons between various models (Table 4.1).

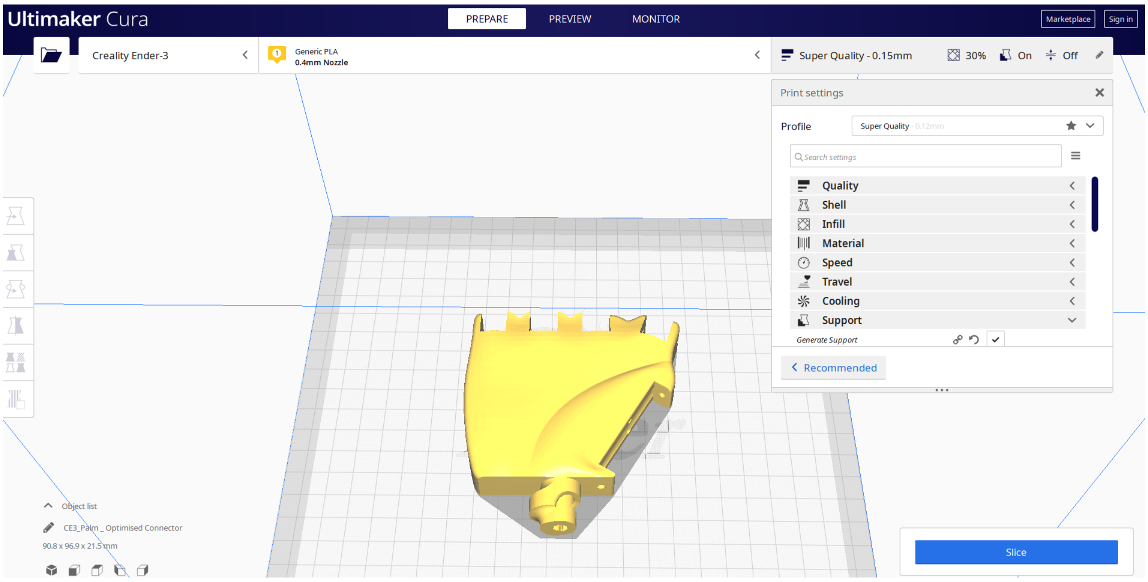
Table 4.1: Open Source models of a myoelectric prosthesis.

Open Source Models	**Characteristics**	**Limitations**
InMoov [51]	- Low cost of production. - 3D printed. - Modify the design prior to printing. - Includes an assembly guide. - One MG995 servomotor for each finger.	- A single degree of freedom. - The servo motors in the fingers occupy the entire space of the forearm.
Elsayed, M [52]	- Low cost of production. - 3D printed. - Modify the design prior to printing. - Six degree of freedom.	- Three servomotors connected to the five fingers of the hand, taking away their independence.

The movements of the chosen Open Source prosthesis model resemble certain movements of a human hand. The prosthesis allows grasping and releasing of objects through flexion and extension of the fingers, movements of pronation and supination of the hand, and flexion/extension of the elbow. Several modifications were made to this model. Among the main ones are:

- Greater ease and independence of each of the fingers with the connection of its servomotor, and
- The use of a single MG995 servomotor for elbow movement.

4.2.2 3D printing settings



Creality Ender-3

Generic PLA
0.4mm Nozzle

Super Quality - 0.15mm 30% On Off

Profile Super Quality - 0.12mm

Generate Support ✓

CE3_Palm _ Optimised Connector
90.8 x 96.9 x 21.5 mm

Figure 4.5: Print settings in Ultimaker Cura version 4.5.

The myoelectric prosthesis was printed on my personal Creality Ender-3 Pro printer. The printing configuration was made in Ultimaker Cura 4.5 software (Figure 4.5). All the necessary profiles and printing characteristics can be determined. In this way, you can choose the type of nozzle, the maximum and minimum temperatures of the printing bed and the extruder, filament thickness, filling and supports, printing and extrusion speed, exterior and interior walls, cooling, among others. Thus, the best configuration is determined that fits the necessary quality concerning time, since the higher the quality, the longer printing time is required. The palm seen in Figure 4.5 took a printing time of approximately 10.5 hours due to quality. The impression of the complete prosthesis took an approximate time of 150 hours.

4.2.3 Materials of myoelectric prosthesis

The material chosen for the myoelectric prosthesis is polylactic acid (PLA) filament, according to the bibliographic review presented in Table 3.1. Due to its hardness, durability, flexibility, difficulty and printing temperature, warpage, solubility, and costs. Besides, one of the most significant properties of PLA is the mechanical response it has compared to other thermoplastic polymers; that is, the resistance of the material to traction [58]. Approximately 800g of the material was used in the 3D printing of all the parts that make up the prosthesis. DOURADO nylon wire was used to connect the three parts of each finger to the SG90 servo motors and using 1 1/2 inch steel headed nails as joints. Also, I used MG995 servo motors to provide movement to the wrist and elbow. Four alkaline batteries of 1.5v and 800mA were connected to power the servomotors, giving a total supply voltage of 6v and a current of 3200mA. Batteries that directly provide this voltage could be used. However, they are larger than a typical alkaline battery, and the battery will not fit inside the prosthesis.

4.3 System Code (Programming)

The acquisition of the EMG signal from the electrodes attached to the arm and connected to the electromyograph's final circuit and through the Arduino Pro Mini allowed configuring the grip and release movements of objects. First, the scaling of the signal read from the analog input is done with the scaling () function. The Arduino board provides values in the range of 0 to 1023, and it is necessary to change this range to the voltage from 0 to 5 V.

The final oscillation range of the standard EMG signal obtained is from 0.2 to 0.5 V. The signal presents maximum peaks that exceed 0.7 V when closing the hand. In this way, it was programmed that if the potential is equal to or greater than 0.7 V, the order is executed for all the servomotors from their initial position to go to their final position. Otherwise, if the maximum peak voltage is less than 0.7 volts, the servo motors will return to their initial position, allowing flexion and extension of the fingers. The programming of the entire project was done in the Arduino IDE Software.

4.3.1 Servomotors calibration

The calibration phase of each finger's servomotors was carried out manually and through the use of the Arduino IDE software. Manually, with the lever that comes inside the servomotor, it was possible to determine the maximum and minimum range of rotation and locate its start and end positions through the Arduino code. These positions can be observed in Table 4.2. Besides, it must be considered that the servomotor bearings are plastic, so an excessive force or rotation outside their range would cause ruptures in them.

Table 4.2: Initial and final positions of the servomotors.

Location	**Inicial Position**	**Final Position**
Thumb	5°	175°
Index	10°	175°
Medium	5°	170°
Ring	10°	175°
Pinky	5°	175°
Wrist	10°	165°
Elbow	10°	100°

Chapter 5

Results and Discussion

Among the most relevant results obtained with the device are:

1. The acquired EMG signals; and
2. The movement of the prosthesis as a function of the acquired EMG signal.

5.1 The Acquired EMG Signals

Figure 5.1 shows that the EMG signal is amplified with 1000 times of gain and differentiated from its two inputs. The amplitude of the digital signal oscillates between 0.35 and 0.55 V.

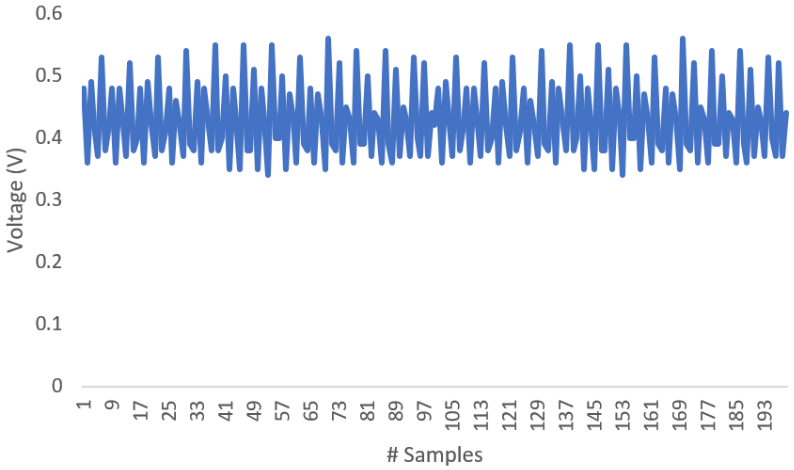


Figure 5.1: Amplified and differentiated EMG signal.

Data were acquired for 2 seconds, with a total of 200 samples. These samples were stored in a ".txt" file and then plotted in Microsoft Excel to improve the graphics' definition. The EMG signal has a high grade of noise due to all the environmental interferences, cables, resistors, and protruding capacitors of the protoboard plaque, incorrect adhesion of the electrodes to the arm, and other artifacts that affect the reading of the signal.

The result of eliminating the high frequencies of over 300 Hz through a low-pass filter is shown in Figure 5.2, where noise and interference decrease and the amplitude range changes compared to the EMG signal in Figure 5.1. However, it is observed that the signal after 30 seconds of reading begins to descend to zero; that is, the signal does not remain constant, and after one minute of reading, the signal disappears.

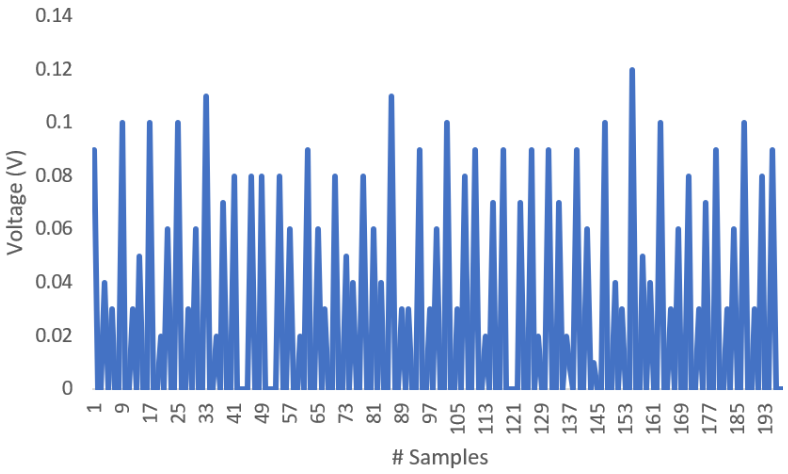


Figure 5.2: EMG signal through a low-pass filter.

The result of reading data from the Arduino board's analog input through the low-pass and high-pass filters (Figure 5.3); that is, with a bandwidth of 10 to 300 Hz. In this way, much of the noise and interference present in the signal was eliminated. To improve the adhesion of the electrodes, they were held with tape on the arm. However, the decrease in the signal is still present.

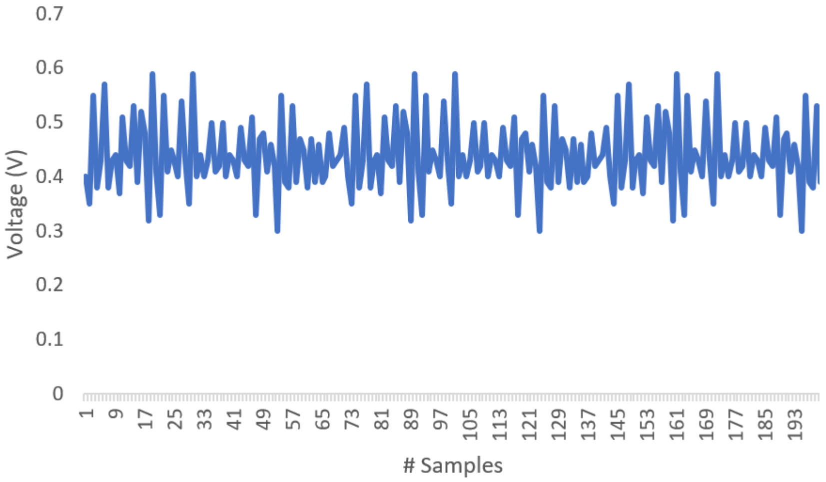


Figure 5.3: EMG signal through the low-pass and high-pass filters.

Finally, the resulting signal is shown in Figure 5.4, after acquiring the EMG signal through the final circuit, where it is amplified, differentiated, and filtered. The EMG signal is kept in a constant oscillation range due to interference caused by the ground connection was controlled.

The resulting EMG signal oscillates in the range of 0.2 to 0.5 V. At the moment of contracting the muscle, the range oscillates from 0 to 1.3 V. Thus, it is possible to send orders to the internal servomotors of the prosthesis to change their position depending on the value of the maximum peak.

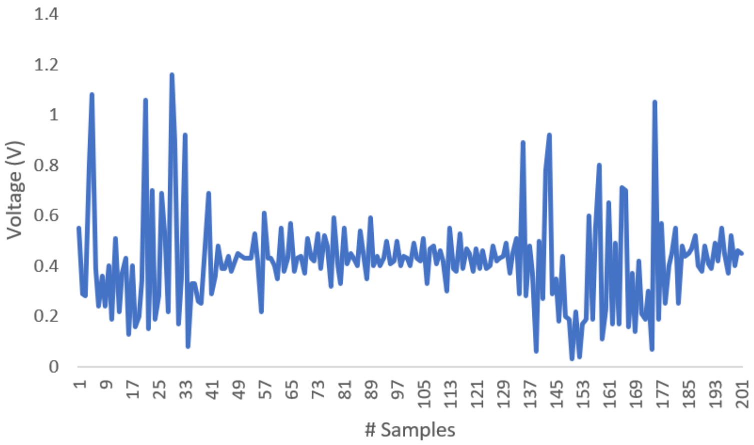


Figure 5.4: EMG signal with two muscle contractions.

5.1.1 Comparison with MyoWare sensor

Figure 5.5: RAW EMG signal from the MyoWare sensor [24].

A comparison was made with the MyoWare sensor to verify the developed circuit's EMG signal's quality. Comparing both raw EMG signals (Figure 5.1 and Figure 5.5), they are nearly identical with a similar oscillation range, and maximum and minimum peaks pronounced mainly at the moment of muscle contraction. Both signals present much interference, which would make it challenging to obtain patterns for a possible application, so the two signals must pass to the filter phase.

5.2 Movement of the Prosthesis as a Function of the Acquired EMG Signal

Figure 5.6 shows the connection of the three parts of each finger of the prosthesis with the servomotors using the DOURADO nylon thread and the steel nails with a head used as joints.

Figure 5.6: Parts of the fingers connected with nylon thread and use of nails for the joints.

Other components that are part of the prosthesis are one SG90 servomotor in each finger (Figure 5.7), one MG995 servomotor in the wrist, and one MG995 servomotor in the elbow.

Figure 5.7: Connection of SG90 servomotors with fingers.

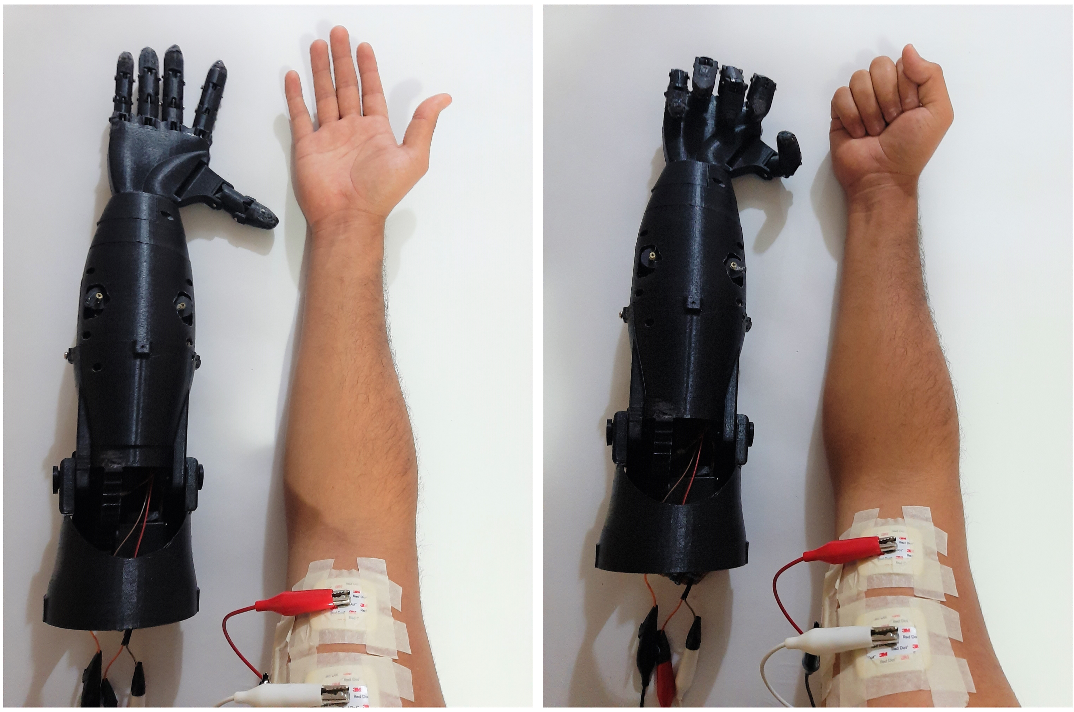
Figure 5.8 shows the possible movements of the developed myoelectric prosthesis.

(a) (b) (c) (d)

Figure 5.8: Movements of the myoelectric prosthesis: (a) pronation of hand and forearm, extension of fingers, and flexion of elbow; (b) supination of hand and forearm, extension of fingers, and flexion of elbow; (c) pronation of hand and forearm, extension of fingers, and extension of elbow; (d) supination of hand and forearm, extension of fingers, and extension of elbow.

5.2.1 Biomechanical analysis

Figure 5.9 shows the operation of the prosthesis's internal servomotors when detecting a growth or decrease of the maximum peak of the EMG signal, allowing flexion and extension of the fingers.



(a) (b)

Figure 5.9: Human arm connected to the myoelectric prosthesis through electrodes: (a) open hand, (b) close hand.

The flexion of each of the human hand fingers starts at 0° and extends to 180°. Figure 5.10 shows the analysis of the initial and final positions of each of the prosthesis fingers.

(a) (b) (c) (d) (e)

(f) (g) (h) (i) (j)

Figure 5.10: Angles of movement of each finger of the prosthesis: (a) thumb finger extended, (b) thumb finger flexed, (c) index finger extended, (d) index finger flexed, (e) middle finger extended, (f) middle finger flexed, (g) ring finger extended, (h) ring finger flexed, (i) little finger extended, (j) little finger flexed.

5.3 Cost Analysis

One of the initial objectives of the project was to develop a low-cost myoelectric prosthesis. For this, the electromyograph circuit and the prosthesis were built with inexpensive and readily available components. Quotes from two electronic stores, as shown in proforma 1 and 2. Table 5.1 shows the total cost of the entire project's raw material shown, which was $ 86.15. To make a cost comparison, only the MyoWare sensor in Ecuador has an approximate cost of $ 70; that is, it has a value of $ 16.15 less than the total cost of this project, it is impossible to buy the rest of the materials with the remaining money.

In Ecuador, the universities are the institutions that mostly focus on the development of prosthesis. However, there are foundations such as GekoFund dedicated to the development of low-cost cosmetic and mechanical prosthetics. Also, Protéus is an Ecuadorian company that develops any high-tech and highly functional myoelectric prosthesis, but its cost is between $ 15,000 and $ 50,000 [59]. Oscar Vargas, in his titling project, designed and built a robotic prototype of a right hand and forearm for prosthetics, the cost of which was $ 3450 [60]. The Instituto Ecuatoriano de Seguridad Social - IESS (Ecuadorian Social Security Institute) in 2018, bought a transradial amputation myoelectric prosthesis for a patient valued at $ 15,000 [61]. After all the bibliographic review shown, it is confirming the low cost of raw materials for the development of this entire project, and it is expected to have a significant impact on the Ecuadorian health system.

Table 5.1: Costs of the raw material for the development of the prosthesis.

Unit	**Material**	**Total Value ($)**
3	Operational amplifiers	2.50
1	Nylon DOURADO	0.60
1	Instrumental amplifier AD620	7.80
15	Resistors (various measures)	0.75
2	Capacitors (various measures)	0.20
1	Perforated bakelite	0.75
2m	Soldering tin	0.80
3	Lizard cables	0.90
1	Arduino Pro Mini	4.00
3	Electrodes	2.25
4	Batteries	10.00
4	Battery connector cables	1.00
5	SG90 servomotors	15.00
2	MG995 servomotors	20.00
800g	PLA filament	17.60
—	Various	2.00
	Total	**$86.15**

Chapter 6

Conclusions

Upper limb amputations cause physical and emotional harm to people due to their total lifestyle change. In underdeveloped countries, access to rehabilitation services is minimal; only 5% of the 650 million people who have a disability worldwide have access to it. Ecuador is not the exception since upper limb prosthesis are very limited, although not exceptionally functional, and its costs are high. It is essential to consider the arm's physiology, the types of amputations, the myoelectric signal generated by muscle contraction, and prosthesis that currently exist, to propose a solution.

I designed and implemented, part by part, every detail of the entire system of a low-cost 3D printed functional transhumeral upper limb myoelectric prosthesis with 6 degrees of freedom. Among the main components that I develop are:

- electromyograph circuit,
- soldering of the circuit in a bakelite,
- modification of the design of the Open Source model of the prosthesis for greater independence of the fingers,
- 3D printing of all parts of the prosthesis in my printer,
- calibration of the servomotors and the movement of the fingers, and

- coupling of the EMG circuit with the internal servomotors of the prosthesis through the programming code.

All the raw material necessary for the project's experimentation and development phase was self-financed.

The EMG signal read through the designed circuit is very similar to that of commercial sensors. The myoelectric prosthesis developed is much more economical compared to prostheses made by some institutions in Ecuador. The prosthesis movements serve one of the basic movements in daily activities, taking and releasing objects.

Underdeveloped countries should improve the health system by investing in technology and raw materials to prepare prosthesis and myoelectric sensors according to the type of amputation. The prosthesis developed is expected to have a significant impact in Ecuador due to the little development in this field and the high cost of acquiring a prosthesis. A prosthesis cannot save a life, but improving the lifestyle of a person who has a disability and can return to their daily activities is priceless.

Chapter 7

Future Perspectives

It is vitally important to improve the electrodes used to obtain the EMG signal since they are disposable, and optimize the battery consumption of the EMG circuit and the prosthesis's internal servo motors.

It is recommended to use sensors with three or more input channels, to identify more patterns in the EMG signal and implement neural networks to make the reading more optimal.

The software could be designed that involves virtual reality to train the person in terms of strength and movements, allowing the person to feel an active part of the process; that is, having full knowledge of what is happening between your arm and the prosthesis.

Using a dynamometer, the prosthesis's grip strength could be achieved since the tension of the nylon thread varies in each finger.

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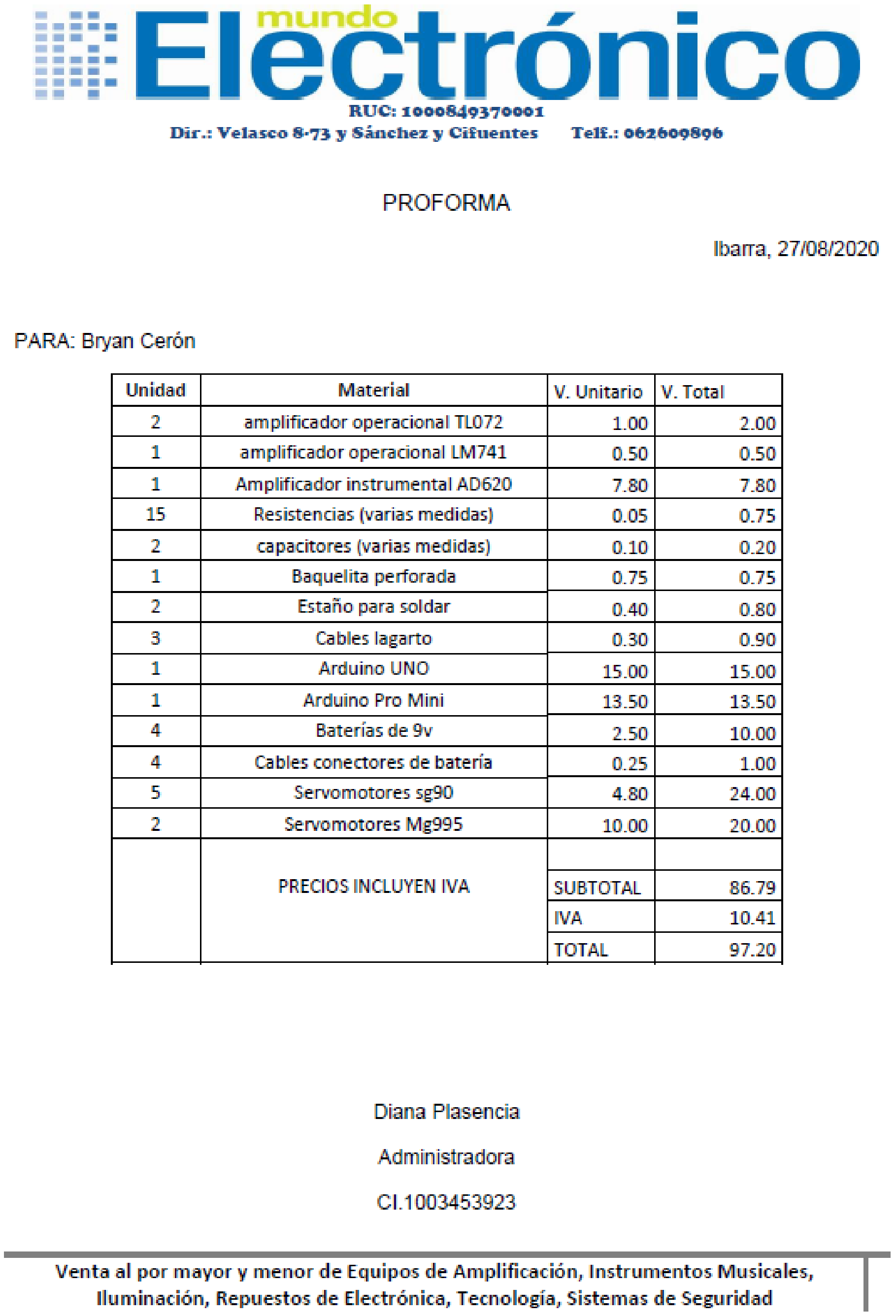
Appendices

.1 Proforma 1



mundo Electrónico

RUC: 1000849370001

Dir.: Velasco 8-73 y Sánchez y Cifuentes Telf.: 062609896

PROFORMA

Ibarra, 27/08/2020

PARA: Bryan Cerón

Unidad	Material	V. Unitario	V. Total
2	amplificador operacional TL072	1.00	2.00
1	amplificador operacional LM741	0.50	0.50
1	Amplificador instrumental AD620	7.80	7.80
15	Resistencias (varias medidas)	0.05	0.75
2	capacitores (varias medidas)	0.10	0.20
1	Baquelita perforada	0.75	0.75
2	Estaño para soldar	0.40	0.80
3	Cables lagarto	0.30	0.90
1	Arduino UNO	15.00	15.00
1	Arduino Pro Mini	13.50	13.50
4	Baterías de 9v	2.50	10.00
4	Cables conectores de batería	0.25	1.00
5	Servomotores sg90	4.80	24.00
2	Servomotores Mg995	10.00	20.00
	PRECIOS INCLUYEN IVA		
		SUBTOTAL	86.79
		IVA	10.41
		TOTAL	97.20

Diana Plasencia

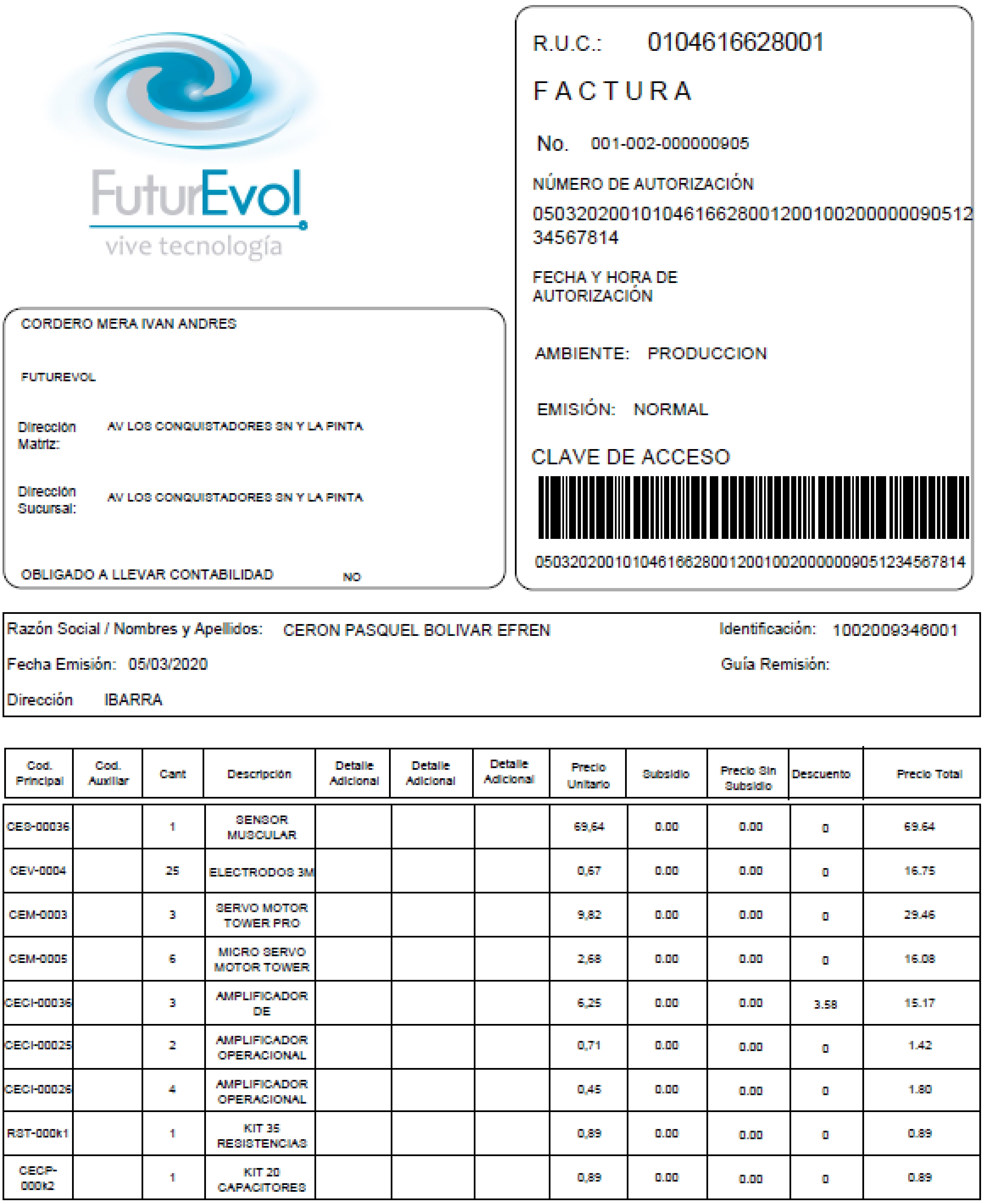
Administradora

CI.1003453923

Venta al por mayor y menor de Equipos de Amplificación, Instrumentos Musicales, Iluminación, Repuestos de Electrónica, Tecnología, Sistemas de Seguridad

Figure 1: Proforma 1.

.2 Proforma 2



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CORDERO MERA IVAN ANDRES

FUTUREVOL

Dirección Matriz: AV LOS CONQUISTADORES SN Y LA PINTA

Dirección Sucursal: AV LOS CONQUISTADORES SN Y LA PINTA

OBLIGADO A LLEVAR CONTABILIDAD NO

R.U.C.: 0104616628001

FACTURA

No. 001-002-000000905

NÚMERO DE AUTORIZACIÓN
050320200101046166280012001002000000905123456781 4

FECHA Y HORA DE AUTORIZACIÓN

AMBIENTE: PRODUCCION

EMISIÓN: NORMAL

CLAVE DE ACCESO
0503202001010461662800120010020000009051234567814

Razón Social / Nombres y Apellidos: CERON PASQUEL BOLIVAR EFREN

Identificación: 1002009346001

Fecha Emisión: 05/03/2020

Guía Remisión:

Dirección IBARRA

Cod. Principal	Cod. Auxiliar	Cant	Descripción	Detalle Adicional	Detalle Adicional	Detalle Adicional	Precio Unitario	Subsidio	Precio Sin Subsidio	Descuento	Precio Total
CES-00036		1	SENSOR MUSCULAR				69,64	0.00	0.00	0	69.64
CEV-0004		25	ELECTRODOS 3M				0,67	0.00	0.00	0	16.75
CEM-0003		3	SERVO MOTOR TOWER PRO				9,82	0.00	0.00	0	29.46
CEM-0005		6	MICRO SERVO MOTOR TOWER				2,68	0.00	0.00	0	16.08
CECI-00036		3	AMPLIFICADOR DE				6,25	0.00	0.00	3.58	15.17
CECI-00025		2	AMPLIFICADOR OPERACIONAL				0,71	0.00	0.00	0	1.42
CECI-00026		4	AMPLIFICADOR OPERACIONAL				0,45	0.00	0.00	0	1.80
RST-000k1		1	KIT 35 RESISTENCIAS				0,89	0.00	0.00	0	0.89
CECP-000k2		1	KIT 20 CAPACITORES				0,89	0.00	0.00	0	0.89

Figure 2: Proforma 2.