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Ergonomic design of a bionic upper-limb prosthesis controlled by electromyographic signals

Diseño ergonómico de una prótesis biónica para miembro superior controlada por señales electromiográficas

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Abstract: This paper presents the design of a bionic prosthesis for the upper limb based on anthropometric measurements and controlled by electromyographic signals. The prosthesis is designed to provide users with the ability to perform cylindrical and pincer-shaped grips to contribute to the reintegration of people with disabilities in their upper limbs into social life and try to find total independence. The mechanical design of the prototype was carried out using Autodesk Fusion 360 software. The design was based on a detailed approach, taking into account the specific needs of the users and the characteristics that would allow optimal functioning of the low-cost prosthesis. Mechanical components, such as joints and the previously mentioned gripping systems, are incorporated, giving users versatility when interacting with various objects. As a result, it was obtained that the designed prosthesis does not exceed 10% of the dimensions of a human hand. Finally, the validation of the 3D printed prototype using PLA plastic with the two grips mentioned above and controlled through bioelectric events using EMG signals is presented.

Keywords: Bionic hand, Structural analysis, Autodesk Fusion 360, EMG signals, anthropometric design.

Resumen: Este articulo presenta el diseño de una prótesis biónica para miembro superior basado en medidas antropométricas y controlada por señales electromiográficas. La prótesis está diseñada con el objetivo de proporcionar a los usuarios la capacidad de realizar agarres tanto cilíndricos como en forma de pinza, con el fin de contribuir a la reintegración de personas con discapacidad en sus miembros superiores a la vida social y tratar de buscar una independencia total. El diseño mecánico del prototipo se llevó a cabo utilizando el software de Autodesk Fusion 360. El diseño se basó en un enfoque detallado, teniendo en cuenta las necesidades específicas de los usuarios y las características que permitirían un funcionamiento óptimo de la prótesis de bajo coste. Se incorporaron componentes mecánicos, como articulaciones y los sistemas de agarre mencionados previamente, lo que brinda a los usuarios una versatilidad al interactuar con diversos objetos. Como resultado se obtuvo que la prótesis diseñada no supera el 10% de las dimensiones de una mano humana. Finalmente, se presenta la validación del prototipo impreso en 3D utilizando plástico PLA con los dos agarres mencionados y controlados a través de eventos bioeléctricos, utilizando señales EMG.

Palabras clave: Prótesis biónica, Análisis estructural, Autodesk Fusión 360, Señales EMG, Diseño antropométrico.

1. INTRODUCTION

In today's society, people with physical disabilities make up a significant and diverse group. The term physical disability, according to the definition of the Ministry of Health, covers those individuals who experience limitations in their mobility and face obstacles to changing or maintaining a body position, as well as manipulating objects autonomously and independently.

The loss of a hand can be devastating and complicated, and the functional limitations after the event are traumatic, causing dysvascularity and neoplasia (uncontrolled growth of abnormal cells or tissues in the body) [1]. According to the National Administrative Department of Statistics (DANE), a significant number of people have been identified in the municipality of Pamplona, Norte de Santander, who do not receive rehabilitation services. In Table 1, it is observed that of 1101 people, 526 indicate that lack of money is why they do not access rehabilitation services [2]. Furthermore, as mentioned in [3], men are significantly more likely than women to lose their hands, with 67% of their upper limbs amputated. Upper limb amputations are the most common during productive working years, with 60% ranging between 16 and 54 years of age.

Table 1: *Population with registration for location and characterization of the People with disabilities*

Reasons as to why no rehabilitation service is received.		Total	
	Total	**Men**	**Women**
Total	1101	507	594
Rehabilitation finished	61	30	31
Believes it is no longer required	60	32	28
Reluctancy	61	29	32
Lack of money	526	244	282
Remoteness from center of attention	27	9	18
There is no one to carry it	37	13	24
No knows	266	124	142
Without Information	63	26	37

Source: *[3].*

Despite prostheses on the market, their accessibility is limited by high costs, justified by technological advances. This scenario has driven the need for research and development projects that focus on the design and construction of robotic hands, resulting in essential contributions to emulating human behavior for object manipulation, as demonstrated in [3-5].

The human hand has a high anthropometric value, is quite complex, and has 25 degrees of freedom (DOF) [5], as illustrated in Fig. 1.

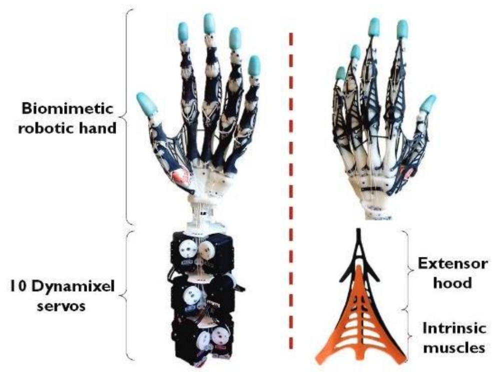

Fig. 1. *The biomimetic robotic hand.*
Source: *[5].*

Overcoming the challenge of replicating human dexterity in robotic systems necessitates the integration of intricate mechanisms, controllers, and actuators within a confined space [5], [6]. In evaluating robotic hand designs, our unique contribution is the proposal of a novel metric that considers the type of grip they can perform. This metric stands out amidst the numerous existing works in the field, underscoring the potential for future studies and advancements in this area [7], [8].

When designing a robotic hand prototype, it is crucial to tailor the types of grip to the specific functional objectives, which are task-dependent [8]. Our research suggests precision grips are particularly advantageous for interaction tasks [9]. We explore various design approaches, such as incorporating actuators in the forearm and transmitting movements through tendons [10] or directly coupling motors to the joints using rod mechanisms that transmit movement through a

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curved profile [11]. These approaches and finger mechanisms that use bars as drive components expand the control possibilities of multi-fingered hands through defined trajectories. Motion transmission devices are necessary to mitigate interference due to space limitations [12].

Another important point that is considered in the literature of previous works is the use of electrodes for the movement of the prostheses. An electrode is a transducer responsible for converting ionic current into electrical current using a non-metallic medium. This device is responsible for recovering the action potential and converting it into an electrical signal to measure and process it later. This process is feasible because skin tissue has properties similar to an electrolyte substance. Its composition includes free ions, allowing it to function as a conductor [13].

One of the key challenges in myoelectric control is generating simultaneous and proportional control signals for motorized hand prostheses with multiple degrees of freedom (DOF) [14]. Our research explores traditional proportional control and on-off switch strategies using surface electromyography (EMG) signals [15], [16]. While biological signals contain crucial information for understanding human body pathologies and behaviors, this information is not readily available in the signal obtained directly from the electrodes [17] due to additive noise from the electrodes and the environment. Preprocessing is necessary to extract the relevant information, involving signal amplification and smoothing methods [18], [19].

Myoelectric prostheses are controlled by an external device that synthesizes the signals and sends them to the control card. They are considered the most advanced rehabilitation devices since they do not require harnesses or suspension means [19]. With the advancement of digital technology, the analysis and processing of biosignals in a digital format have become more convenient [20]. It is necessary to convert the analog signal to a numerical form using an analog-digital converter to achieve this.

This paper focuses on designing a robotic hand prototype to meet the needs of users with physical disabilities, offering two types of grips to improve their quality of life. The design is based on the emulation of the complex human hand. In addition to addressing aspects such as the choice of materials and components for the design, the static analysis of the robotic hand, the implementation of circuits, and signal filtering are carried out. The process of connecting the electrodes to an analog-digital converter and the configuration of filters for the processing of EMG signals is detailed. These elements are fundamental for the functionality and precision of the device, allowing a more precise interpretation of the myoelectric signals and greater effectiveness in manipulation. Finally, future work contemplates the independent implementation of each finger to improve the precision in manipulation further and adapt the prosthesis to the specific needs of the users.

2. BIONIC PROSTHESIS DESIGN

This section describes the design process that results in the three-dimensional representation of the prototype of the robotic hand.

2.1 Preliminary conditions

The proposed robotic hand, a pioneering prototype, utilizes a unique mechanism of four connected links for the movement of each finger. This innovative mechanical system, comprising three phalanges in each finger (excluding the thumb), seamlessly integrates, enabling the simultaneous movement of these fingers. This groundbreaking design offers a variety of grips, with the' pinch and grasp' being a standout feature. This grip type allows the user to manipulate objects using two fingers, mimicking the pinching and holding action of the human hand, as depicted in Fig. 2 and Fig. 3.

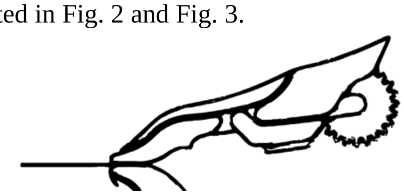

Fig. 2. *Pinch-type grip.*
Source: *Self-made.*

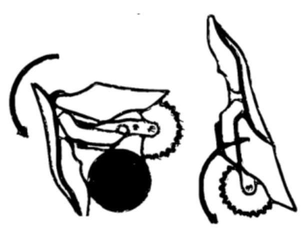

Fig. 3. *Object holding type grip.*
Source: *Self-made.*

For the prototype design, high torque MG996 servomotors are used, along with two MG90s servomotors, to control the movement of the index finger, thumb, and the remaining fingers together. These servomotors were chosen because their size and weight suit the required application. In addition, a 1nF ceramic capacitor was installed in each actuator to prevent possible overloads.

2.2 Design of the middle, ring, and little finger

The decision was made to design a rigid mechanism between the different forms of actuation and motion transmission mechanisms to move the robotic joints. It was decided to implement a finger mechanism with rigid transmission. The index finger requires an actuator to be activated, as does the thumb; otherwise, the remaining fingers, ring, index, and little finger, which are activated by a servomotor where the transmission of movement comes from the little finger.

The measurement between the top and bottom of the middle, ring, and little fingers is equal to 24.90mm, so it is similar to the human finger, as shown in Fig. 4.

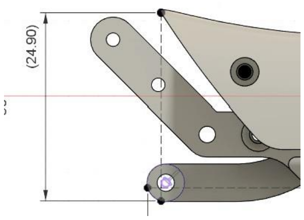

Fig. 4. *Height of the middle finger, ring finger and little finger.*
Source: *Self-made.*

The distance of the middle finger, ring finger, and little finger is the same as shown in Fig. 5, trying to be as similar to a human finger as possible; this is shown in Fig. 6, where the comparison of a hand is made scanned human and a designed finger.

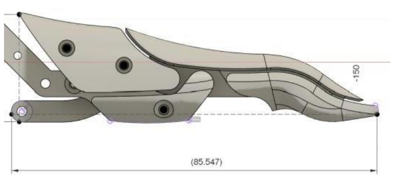

Fig. 5. *Length of the middle finger, ring finger and little finger.*
Source: *Self-made.*

Fig. 6. *3D scan of a human hand and middle, ring and little finger.*
Source: *Self-made.*

2.3 Movement transmission for the index finger

In the design of the index finger, the movement is transmitted directly through a gear coupled to the finger and a gear in the MG996 servomotor, as shown in Fig. 7 and Fig. 8.

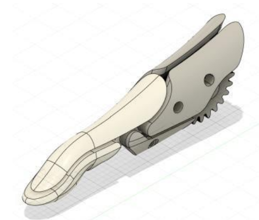

Fig. 7. *3D design of the index finger.*
Source: *Self-made.*

The index finger comprises seven pieces, as seen in Fig. 8. Pieces 1, 2, 3, and 7 are similar to those that make up the middle, ring, and little fingers. Piece 4 closes and secures the mechanism so that piece 6, which has a central hole, ensures the proper position of the finger. Finally, part 5 presents a gear made up of twenty-six teeth, which is the one that receives the movement from the servomotor to guarantee movement.

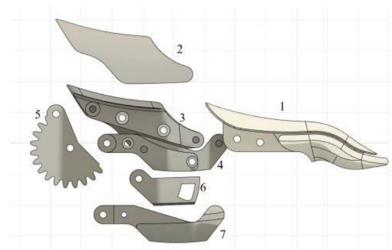

Fig. 8. *Numbering of parts that make up the index finger.*
Source: *Self-made.*

2.4 Transmission of movement of the middle, ring, and little fingers

Two tiny links interconnect the articulated mechanism of the middle, ring, and little fingers. These links facilitate the smooth transmission of motion from the servomotor, as shown in Fig. 9, enabling coordinated and precise operation of the fingers.

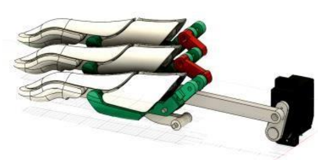

Fig. 9. *Right lateral view of the transmission of movement of the little finger, ring finger and middle finger.*
Source: *Self-made.*

The transmission of the index finger is achieved by two gears: one located in the servomotor, with 26 teeth, and another in the index finger. This is evident in Fig. 10 and Fig. 11.

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Fig. 10. *Movement transmission of the index finger.*
Source: *Self-made.*

Fig. 11. *Index finger mechanism.*
Source: *Self-made.*

3. STRUCTURAL ANALYSIS

This hand comprises several materials, mainly polylactic acid (PLA). Table 2 presents the properties of the PLA plastic used in the prototype design entered into the Autodesk Fusion 360 software for structural analysis. The different parts used in the prototype are listed and shown in Fig. 8, Fig. 12, and Fig. 13.

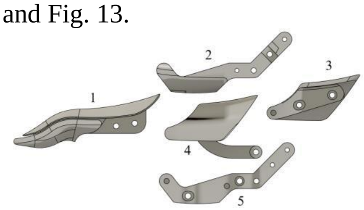

Fig. 12. *Numbering of parts of the middle finger, little finger and ring finger.*
Source: *Self-made.*

Fig. 13. *Numbering of thumb pieces.*
Source: *Self-made.*

Fig. 14 presents the result of the lower and upper casings used in the design.

Fig. 14. *Lower and upper casings.*
Source: *Self-made.*

With the materials defined in the Autodesk Fusion 360 software, where the hand was designed, a structural analysis is carried out for pieces 2, 3, 4, and 5, which are the ones that receive the most significant load when performing the grip-type grip. Objects are presented in Fig. 3. For this, the masses of the robotic hand are calculated and presented in Table 3.

Table 2*: Properties acid polylactic*

PLA plastic	
Density	1.3 E^03 kg / mm^3
Young's modulus	3500MPa
Poisson's ratio	0.39
Yield point	55MPa
Maximum tensile strength	49MPa
Thermal conductivity	0.13 W/M °C
Vitrification temperature	(52 – 60) °C
Specific heat	1800 J / (kg °C)

Source: *self-made.*

Table 3: *Masses of hand robotics*

Component	*Material*	*Amount*	*Mass (g)*	*Partial of masses (g)*
Upper Case	PLA plastic	1	43.27	43.2
Bottom shell	Plastic PLA	1	72.15	72.15
Piece 1	Plastic PLA	3	5.71	17.13
Piece 2	Plastic PLA	3	1.87	5.61
Piece 3	Plastic PLA	3	1.72	5.16
Piece 4	Plastic PLA	3	2.68	8.04
Piece 5	Plastic PLA	3	1.70	5.1
Index 1	Plastic PLA	1	5.41	5.41
Index 2	PLA plastic	1	2.49	2.49
Index 3	Plastic PLA	1	2.44	2.44
Index 4	Plastic PLA	1	1.31	1.31
Index 5	Plastic PLA	1	1.27	1.27
Index 6	Plastic PLA	1	0.80	0.80
Index 7	Plastic PLA	1	1.32	1.32
Thumb 1	Plastic PLA	1	20.44	20.44

Thumb 2	Plastic PLA	1	2.10	2.10
Thumb 3	Plastic PLA	1	1.29	1.29
Thumb 4	Plastic PLA	1	1.92	1.92
Thumb 5	PLA plastic	1	7.26	7.26
Thumb 6	Plastic PLA	1	1.64	1.64
MG90S	Compound	2	13.4	26
MG996R	Compound	1	55	55
	Total mass (g)			**285.5**

Source: *Self-made.*

3.1 Analysis of the index finger assembly

Fig. 10 shows that the motor will take up much space, which is essential for the pinch-type grip. The maximum weight it supports is 1.5 kg, which, when multiplied by gravity, gives us a force of 14.7N that can be located in each proximal phalanx of the set of fingers supported. With this force, a static analysis is developed in Autodesk Fusion 360 to perceive the displacements the piece physically suffers, shown in Fig. 15.

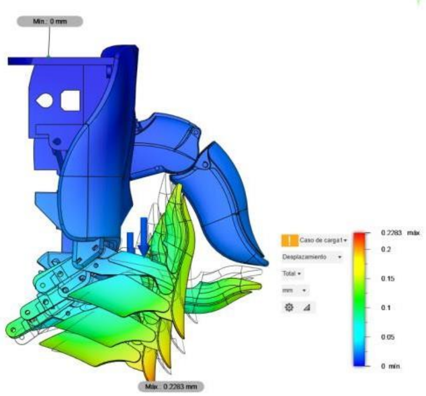

Fig. 15. *Displacement analysis of the finger set.*
Source: *Self-made.*

Although the displacement analysis shows that the part partially moves a distance of 0.2283mm, it should not cause alarms since the analysis allows us to observe where the part will fail given an ideal weight of 1.5 Kg since the composition of the parts is PLA.

4. ELECTROMYOGRAPHIC SIGNAL PROCESSING

This section describes the filtering process of the electromyographic (EMG) signal and the conditioning circuit's design for the prototype's actual implementation.

4.1 Preliminary concepts

The human body relies on bioelectrical events to properly function, underscoring their significance. The ability to measure, comprehend, and analyze these electrical signals has paved the way for the creation of various devices, notably the electrocardiograph, the electroencephalograph, and the electromyograph [21].

The heart often called the primary machine that powers life, generates a unique electrical pattern with each heartbeat. The electrocardiograph (ECG) captures, records, and amplifies this heart's electrical activity through electrodes placed on the four extremities and in six positions near the chest. It is a crucial tool for recording and analyzing this cardiac electrical activity [22], as depicted in Fig. 16. The ECG signal comprises distinct phases, identified by the letters P, Q, R, S, and T.

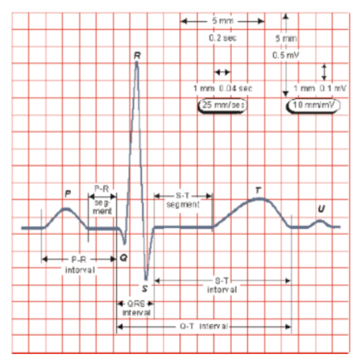

Fig. 16. *Electrocardiogram (ECG).*
Source: *[22].*

The brain, the supreme organ of thought and coordination, also emits electrical signals that can be recorded and analyzed using the electroencephalograph (EEG). This device measures electrical currents generated by nerve cells in the brain, providing a graphical representation of brain activity in the form of brain waves [23], as illustrated in Fig. 17.

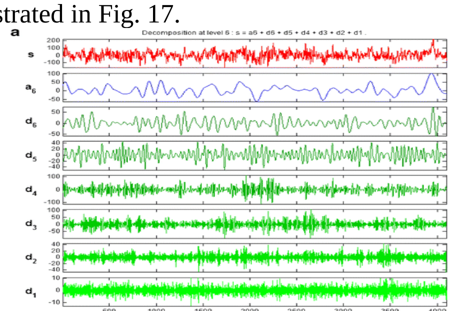

Fig. 17. *Electroencephalogram (EEG).*
Source: *[23].*

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On the other hand, electromyography is responsible for movement and motor function; it also generates electrical signals that can be captured and analyzed using the electromyograph (EMG) [24]. This device records the electrical activity of muscles during contraction and relaxation, providing information on muscle function and activity, as evidenced in Fig. 18.

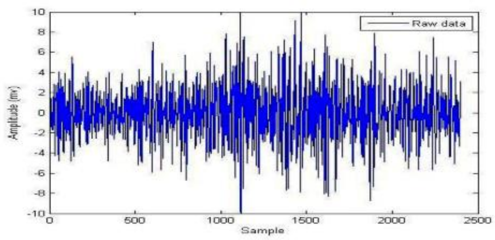

Fig. 18. *Electromyography (EMG).*
Source: *[24].*

Table 4 shows the different typical values of the bioelectric signals present in the body taken from different research works [25].

Table 4: *Typical values of bioelectric signals*

Place	Record name	Amplitude	Bandwidth [Hz]
Cells	Electrogram (EG)	50 – 100mV	DC 1000 - 10000
Heart	Electrocardiogram (ECG)	2 – 3 mV	0.05 – 250
Brain	Electroencephalogram (EEG)	5 – μ300V	0.1 – 100
Muscle	Electromyogram (EMG)	0.1 – 5mV	50 – 5000
Eye	Electrooculogram (EOG)	50V μ– 350mV	0.1 – 10
Stomach	Electrogastrogram (EGG)	10 – 1000 mV	DC – 1

Source: *[25].*

There are different types of electrodes. First, we find the superficial electrodes that adhere to the skin with a conductive gel and capture electrical signals to evaluate neuromuscular or brain function. On the other hand, percutaneous electrodes, known for their precision, are inserted directly through the skin to obtain accurate readings in techniques such as electromyography.

In this research, the method of surface electrodes with conductive gel, a highly effective approach, was used, allowing the capture of EMG signals [26]. A raw signal is obtained when capturing myoelectric or electromyographic signals, which are complex to manipulate and interpret, as represented in Fig. 19.

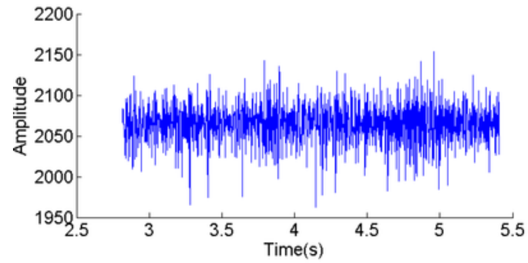

Fig. 19. *Raw EMG Channel 1.*
Source: *Self-made.*

4.2 Signal filtering

Different filters were used to process the EMG signals. Table 5 [27] details the evaluation of each filter and is classified into two categories: ideal or non-ideal for the specific task. This research used filters based on average and passes under an exponential moving average.

Table 5: *Filters used for EMG signal processing. * Ideal, ** Not ideal*

Filters type	Biomimetic prosthesis	Bionic prostheses
Simple averager	**	*
Impulse response filter	*	*
Moving average filter	**	*
Average based filter	**	*
	**	*
Filter pass under exponential moving average	**	*

Source: *Self-made.*

4.3 Methodology for EMG signal processing

When the user performs a muscle contraction at the level of the forearm, whether pressure or flexion [28], an analog signal is generated from the muscle, which follows the methodology presented in Fig. 20 for processing the electromyographic signal (EMG).

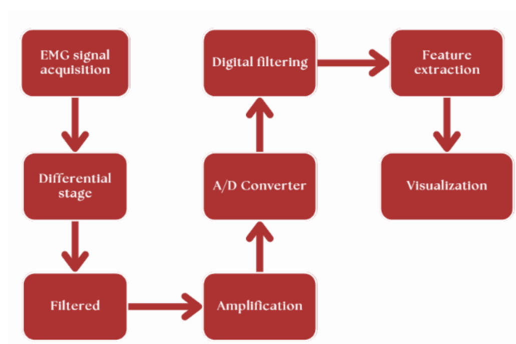

Fig. 20. *EMG signal methodology.*
Source: *Self-made.*

The moving average-based filter (equation (1)) smooths data and reduces noise. Unlike the simple averaging filter, this filter assigns variable weights to past and present values, giving greater weight to recent data. This allows a faster adaptation to change in the signal, providing a smoother and more stabilized output [29].

We can observe how the behavior of the variable is in equation (1), where y[n] is the filtered signal, M is the number of samples, n is the iterator, and k is a constant.

$$y\,[n] = \frac{1}{M}\sum_{i=0}^{M-1} x[n-k] \qquad (1)$$

For the second filter (equation (2)), the exponential moving average low-pass filter was programmed, which is a filter where variable weights are assigned to the past and present data, giving greater importance to the most recent observations [30], unlike simple moving average, where all data has the same weight.

$$S(t) = \begin{cases} Y(0) & t = 0, \\ \alpha Y(t) + (1-\alpha)S(t-1) & t > 0, \end{cases} \qquad (2)$$

where $S(t)$ is the filtered signal, α is a factor that goes from 0 to 1, $Y(t)$ is the data read at that moment, and $S(t-1)$ is the data at the previous time. Fig. 21 shows the behavior of the raw signal and the filters mentioned above.

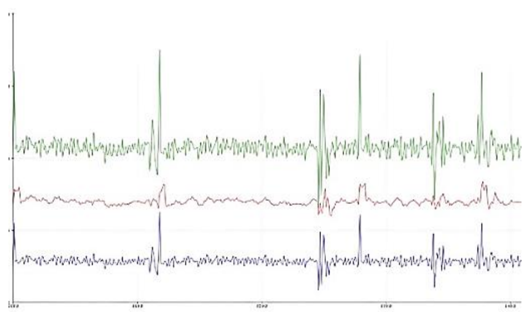

Fig. 21. *Processed EMG signals. Green color (raw signal), Red color (signal with average-based filter) and Blue color (signal with exponential moving average low-pass filter).*
Source: *Self-made.*

4.4 Signal conditioning circuit for real-time system

The three electrodes connect directly to the analog and digital converter (ADC) terminals. Two electrodes were connected to two differential channels, while the last was connected to the ground. Then, the ADC was configured at 24-bit resolution, and the different filters defined in Equation (1) and Equation (2) were programmed.

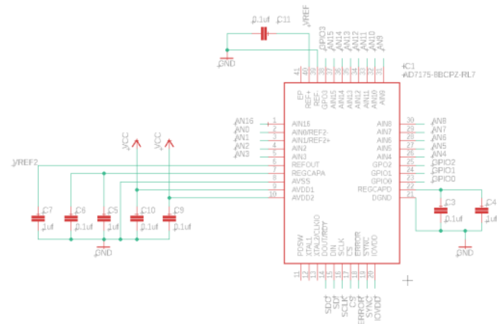

Fig. 22. *Digital analog converter circuit.*
Source: *Self-made.*

5. RESULTS AND DISCUSSIONS

The implementation of the concepts described in sections 2, 3, and 4 results in the prototype of the trans-radial prosthesis, shown in Fig. 23. The prototype has a total dimension of approximately 350 mm, including the display stand socket measuring 180 mm. It is important to mention that the servomotors that activate each joint are located inside the palm, as presented in Fig. 10.

Fig. 23. *Image of the real and rendered prototype.*
Source: *Self-made.*

A pinch-type grip is observed in Fig. 24 (a), while in Fig. 24 (b), an object-holding type grip is presented. Myoelectric signals detected with the electrodes can control these two types of grips.

(a) (b)

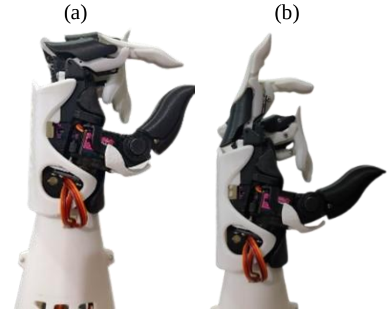

Fig. 24. *Prototype assembly (a) Pinch grasp, (b) Object grasping.*
Source: *Self-made.*

To test the validity of the prototype, an experiment was carried out where a user gave an order to the prosthesis to open and close the hand using myoelectric signals. The results are shown in Fig. 25(a) and Fig. 25(b).

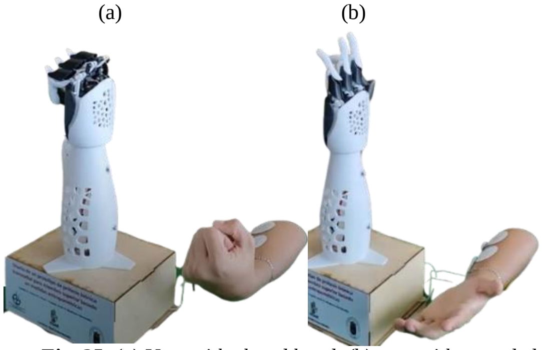

Fig. 25. *(a) User with closed hand, (b) user with extended fingers.*
Source: *Self-made.*

To observe the multimedia resource that shows the operation of the prototype and its behavior in real-time, see [31].

The robotic hand's precision was a standout feature during the tests, as it opened and closed its fingers with natural fluidity. A slight delay of 0.7 seconds was noted in the signal to open and close the fingers, A result of the myoelectric sensor's noise elimination process. To further underscore the hand's reliability, a practical test was conducted with a weight of 2.0 Kg, which the prototype handled with ease. This successful performance validates the hand's ability to exceed its target load of 1.5 Kg and instills confidence in its safety and durability.

6. CONCLUSIONS

This paper introduces a novel bionic upper limb prosthesis prototype design featuring a unique form of movement transmission through an articulated mechanism. The use of polylactic acid (PLA) for the construction of the prototype, while common in prostheses, poses limitations on the user's activities.

The identification of possible failures due to deformation and validation of the design was demonstrated through structural analysis, ensuring that the robotic hand maintains its functionality and shape during use.

Implementing filters, notably the average-based filter and the exponential moving average low-pass filter, has proven highly effective in filtering electromyographic (EMG) signals, showcasing the practical application of our research.

The real prototype was implemented using the design presented and generating the pinch-type grip and object holding.

Looking ahead, our future work aims to implement independent activation of each finger, enabling precise manipulation of each one individually. Additionally, we propose to develop the prototype in Nylon (PA), an ideal material for prostheses and other parts in contact with the skin, further enhancing its usability and comfort.

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