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Bio-Mechatronics Development of Robotic Exoskeleton System With Mobile-Prismatic Joint Mechanism for Passive Hand Wearable-Rehabilitation

Mariela Vargas [1, 2], J. Mayorga [1], B. Oscco [1], V. Cuyotupac [1], A. Nacarino [1], D. Allcca [1], L. Gamarra-Vásquez [1], G. Tejada-Marroquin [1], M. Reategui [1], R. R. Maldonado-Gómez [1], Y. Vasquez [1], Daira de la Barra [1], P. Tapia-Yanayaco [1], Sandra Charapaqui [1], Milton V. Rivera [1], R. Palomares [3], M. Ramirez-Chipana [1, 4], Jorge Cornejo [1, 5], José Cornejo [6*], Jhony A. De La Cruz-Vargas [1]

[1] *Institute of Research in Biomedical Sciences (INICIB), Universidad Ricardo Palma, Lima, Peru.*

[2] *Center for Space Systems (C-SET), Latin America.*

[3] *Research Group of Advanced Robotics and Mechatronics (GI-ROMA), Universidad Ricardo Palma, Lima, Peru.*

[4] *Hospital Nacional Edgardo Rebagliati Martins, EsSalud, Lima, Peru.*

[5] *Mayo Clinic, United States.*

[6] *Universidad Tecnológica del Perú, Lima, Peru.*

Abstract

The World Health Organization (WHO) estimates that 15 million people are affected by stroke each year, causing deterioration of the upper limb, which is reflected in 70-80% of them, decreasing the performance of daily activities and quality of life, mainly affecting hand functions. Thus, the purpose of this study is to present a high-quality alternative to recover muscle tone and mobility, consisting of a hand-exoskeleton for passive rehabilitation. It covers a motion protocol for each finger and pressure sensors to give a safety pressure range during the gripping function. The bio-design method covers standards (ISO 13485 and VDI 2206) based on biomechanic and anthropometric fundamentals, where Fusion 360 was used for mechanical development and electrical-electronic circuit schematics. The prototyping process was based on 3D printing using polylactic acid (PLA); also, the actuators were servomotors DS3218, the pressure sensors were RP-C7.6-LT, and the microcontroller was Arduino Nano. The system has been validated by the Institute of Research in Biomedical Sciences (INICIB) at the Ricardo Palma University, where the novelty of this work lies in the introduction of a new mobile-prismatic joint mechanism. In conclusion, favorable results were achieved regarding the complete flexion and extension of the fingers (91.6% acceptance rate, tested in 100 subjects), so the next step proposes that the wearable device will be used in the Physical Medicine and Rehabilitation Departments of Medical Centers.

Keywords:

Engineering Design;
Medical Mechatronics;
Hand Rehabilitation;
Exoskeleton;
Stroke.

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1- Introduction

According to the World Health Organization (WHO), there are approximately 15 million survivors affected by stroke, and between 70-80% have involvement of the upper extremities [1], which is one of the main healthcare problems worldwide. It can cause a loss of physical strength on one side of the body, paralysis, or hemiplegia, affecting daily

* **CONTACT**: doctor.engineer@ieee.org

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living abilities [2]. A multicenter cross-sectional study found that the main consequences that affect the quality of life of someone who has survived a stroke are hemiplegia, a body disorder in which there is paralysis on one side of the body, followed by dysarthria and facial palsy, as reflected in Table 1 [3]. In most cases, a notable motor loss of the upper limb is reflected, reducing the standard of living and at the same time increasing the costs of rehabilitation therapy, since it requires the attention of a multidisciplinary team, is expensive, and has a slow treatment time. The established treatment for people with stroke involves the practice of repetitive tasks accompanied by physiatrists and rehabilitation doctors in order to improve precision, range of hand movement, and strength [2, 4].

Table 1. Percentage of complications after stroke

Characteristics	N (%)
Complications after stroke:	
Hemiplegia	129 (33.8%)
Dysarthria	92 (24.1%)
Facial palsy	13 (3.4%)
Trouble seeing	17 (4.5%)
Paresthesia	13 (3.4%)
Cognition problem	10 (2.6%)
General weakness	15 (3.9%)
First-ever stroke	**319 (83.5%)**

The loss of hand movement represents a primary disability caused by increasing age, inadequate eating habits, and more serious diseases such as stroke, which can significantly affect the primary functions of the parts of the hand, mainly the muscles and their functions of flexion, extension, abduction, and adduction. The hand is a complex and versatile instrument that allows humans to interact with the world around them more easily: grasping, touching, squeezing, feeling, and communicating are essential activities in daily life at home, work, and school. In addition to this, hands are essential tools in interpersonal relationships. All these particularities make it a cutting-edge topic with vast potential for the creation of new robotic rehabilitation systems [5-8] and medical robotics [9-13]. Currently, there are clinical studies that revealed a notable improvement in the hand-motor functions of stroke patients who have continuous robotic assistance in their treatment, such as performing intense repetitive hand movements [14].

For all of the above, robotic exoskeletons have been proposed as a high-quality alternative to recover mobility and precision in repetitive movements [15]. There are 3 types of rehabilitation treatment: active, passive, and assisted: Passive rehabilitation has a type of active mechanism that allows patients to be treated effortlessly; this is because the robotic system assists the patient in the movement of the arms, muscles, and joints, which prevents stiffness of the patient's joints [16, 17]. On the other hand, active rehabilitation involves physical effort to move, since the design used is through a passive mechanism. That is, exoskeletons maintain the patient's resistance to motion and strengthen the muscles, thus stimulating the brain to improve the sending of neuronal signals [18]. This means that this type of rehabilitation is used when there is muscle atrophy due to reduced movement. In addition, assisted rehabilitation is when the exoskeleton helps the patient exercise their limbs by remaining balanced against an object, which is beneficial to improve muscle strength, reduce movement recovery time, and achieve functional independence through routine programming [18-20].

Some examples of the aforementioned are the interactive hand exoskeleton for both passive and active rehabilitation, iHandRehab, which is bidirectional for passive movement and applies virtual force feedback to the finger as a haptic device for active mode [21, 22]. Likewise, within a passive and assisted rehabilitation approach, there is the Tenodesis Induced Grip Exoskeleton Robot (TIGER) that has assistance as needed (AAN); it has a mechanism responsible for detecting the movement of the wrist, linking it to the hand and forearm, to cause a radial-ulnar deviation that finally leads to the flexion movement of the joint [23, 24]. This manuscript is focused on passive hand rehabilitation with the use of orthosis in patients who have suffered a stroke; various studies on the use of exoskeletons show a significant improvement in the recovery of hand functions, among other things, as shown in Appendix I - Table A.

1-1- Hand Biomechanics and Clinical Background

1-2- a. Anthropometric Analysis of the Hand

The wide range of motion, the ability to achieve fine movements, the anatomical complexity of the hand, and the delicacy of its structure are some of the main reasons why the hand is one of the most complex biomechanical systems in the world. Therefore, for the size and shape of the proposed exoskeleton pieces, the anthropometric measurements of the hand have been taken into account, both dynamic and static in the design, to provide them with the greatest possible ergonomics and allow the necessary movements for the rehabilitation exercises [25].

The exoskeleton was designed using reference data, considering the variability and heterogeneity of people's hands. To do this, information extracted from a study that used the measurements of the hands of its authors belonging to the American continent was used, so A1, A2, A3, A4, A5, A6, A7, A8, A9 are the authors' data of the previous study, $\bar{x}$ being the average of all of them, for this, the indicators used are described below: wrist circumference (WC), wrist width (WW), hand length (HL), hand width (HW), palmar length (PL), palmar width (PW), and the lengths for each digit (TLDi) as shown in Table 2 and Figure 1 [26].

Table 2. Hand anthropometric measurements [26]

Hand Measure (cm)	A1	A2	A3	A4	A5	A6	A7	A8	A9	$\bar{x}$
Hand Length - HL	19.0	19.0	18.0	16.5	18.0	17.9	19.0	18.8	18.0	18.5
Palmar Length - PL	11.0	10.5	11.0	9.0	10.6	10.5	11.0	10.6	10.0	10.4
Hand Width - HW	9.7	10.0	10.0	9.0	10.2	10.3	10.0	11.0	10.0	9.9
Palmar Width - PW	7.4	8.8	8.5	7.5	8.9	7.5	8.8	10.0	8.5	8.6
Wrist Circumference - WC	16.4	16.0	18.0	17.0	18	15.2	16.0	17.8	15.5	17.0
Wrist Width - WW	6.1	6.0	7.0	6.0	6.4	6.6	7.0	6.9	6.0	6.3

The total lengths of each finger (TLDi) were obtained by measuring the lengths of the metacarpals of each finger (MCLi) extracted from hand dimensions and the length of each finger (DLi) according to the anatomical plane, and to take these measurements, 3 reference areas were taken into account: first, the lines that are marked when flexing the wrist on the palmar side (PL); second, the lines that form in the digitopalmar skin folds; lastly, the edge of the distal end of each digit [26]. Then, the intersection of the reference areas was measured following the direction of each finger in the extended position. In this way, the dimensions considered for the LTDi were obtained, and they are mathematically represented with the formula, where TLDi equals MCLi plus DLi, as shown below in Equation 1.

$$TLDi = MCLi + DLi \tag{1}$$

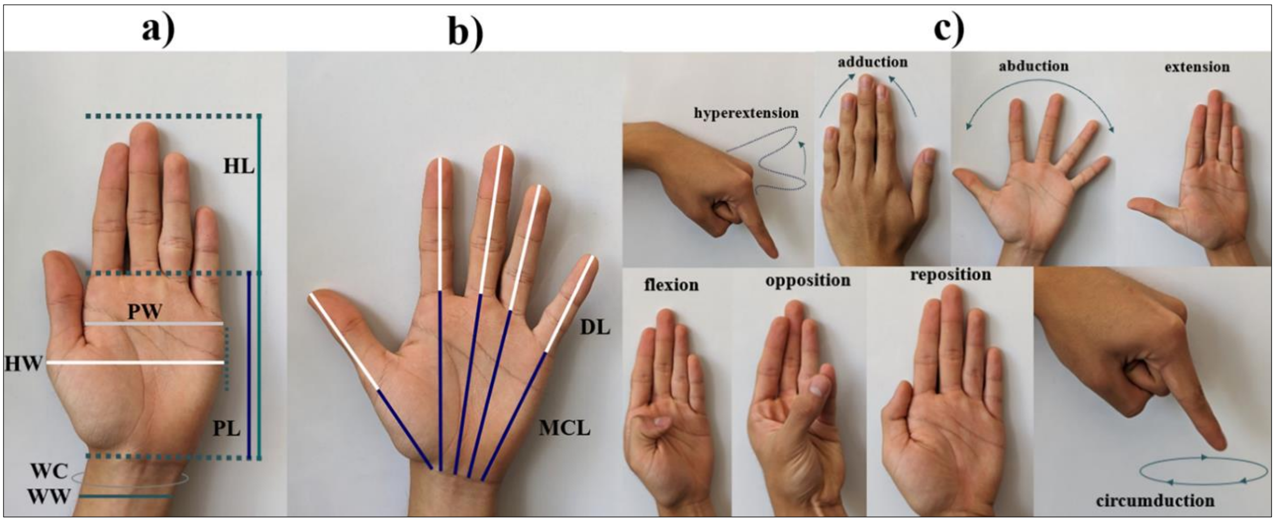

Figure 1. The graphic references of the anthropometric measurements are shown in a) Referential measurements (HL, PW, HW, PL, WC, and WW); b) Referential lengths of each finger (DL: Finger length and MCL: Metacarpal Length); and c) Finger movements: Hyperextension, adduction, abduction, extension, flexion, opposition, reposition, and circumduction.

Due to the complexity of hand's finger movements, as shown in Figure 1, the exoskeleton has been adapted to consider the movements of the hand joints, hand bones, hand muscles, and grip strength, principally all the data of a left hand with a focus on the two main motions: extension and flexion.

1-3-b. Biomechanical Protocols

The device must follow protocols to check the integrity and correct functioning of the upper extremity for the correct conduction of the device; in this sense, it contains a series of pre-established movements to translate biomechanical signals to the apparatus. For this study, all of the fingers are characterized except the little finger, since that finger is anatomically united with the ring digit. In that way, the activation protocol and the evaluation protocols are established. The first consisted mostly of the assignments and start-up of the device under the supervision of the designers, thus seeking passive rehabilitation. Along with the explanation, the parameters and guidelines will be evaluated simultaneously in relation to the necessary actions to be recorded. The second proves that the exoskeleton can perform finger extension and flexion movements. In other words, the device, along with the protocols 1° up to 6°, realized those types of movements. By way of explanation, the ring finger descends from the neutral horizontal plane of the hand (hand in prone position), which refers to flexion; otherwise, if the ring finger ascends from the position of flexion to the neutral position, it would refer to extension, as shown in Figure 1c. These must be interdependent with each other since their execution must not affect or be confused with another, but in turn, they must operate simultaneously to execute daily activities. These movements are also based on the biomechanics of the upper extremity, specifically the angles formed by the joints. Therefore, the evaluation protocols consist of the following cases as shown in Table 3.

Table 3. Evaluation protocols

Number	Motion
1	Perform the flexion and extension movement of each finger independently from the index to the ring finger. Note: The little finger cannot make independent flexion movements, since it is anatomically united with the ring finger.
2	Perform the 2-finger flexion and extension movement on 2 fingers: o First: the thumb + the index finger. o Second: the middle finger + the ring finger. o Third: the ring finger + the little finger. o Finally: back to the thumb.
3	Perform the 3-finger flexion and extension movement on 3 fingers: o First: the thumb + index finger + middle finger. o Second: the index finger + the middle finger + the ring finger. o Third: the middle finger + ring finger + little finger. o Finally: back to the thumb.
4	Perform the flexion and extension movement of 4 fingers: Index finger + middle finger + ring finger + little finger.
5	Perform the flexion and extension movement of the 5 fingers: Closing and opening the fist.
6	Hold an object (canned drink) with your hand.

1-4- Related Technologies

This study starts with a summary that covers the state-of-the-art of published projects, which describes some features that have been useful in defining the components of the robotic wearable exoskeleton:

Regarding the mechanical system, it can be focused on three main segments: actuators, mechanisms, and mechanical design software. In the vast majority of the articles analyzed, the actuators control the rigid elements of the exoskeleton by employing artificial tendon traction (steel or nylon cables). This traction was performed by direct current (DC) motors (27% = 8 of 30 papers), servomotors (17% = 5 of 30 papers) [24], as well as linear actuators (27% = 8 of 30 papers). Among the most widely used electromechanical actuators, the Tower Pro servomotor SG90 stood out for its accessibility, low weight (9g), and small size (23.0 × 12.2 × 29.0 mm) [27, 28]. Likewise, the Tower Pro servomotor MG996R is known for its high torque (11 kgf·cm) when exerting the flexion and extension movements of the exoskeleton [29]. In the remaining articles analyzed, linear actuators such as the Firgelli L16 linear motors [30], together with the PA-07 Micro Linear Actuator [31] and the Actuonix L12-R [32], were used. While the most commonly used materials were polylactic acid (PLA) and thermoplastic polyurethane (TPU) [33]. The weight of the system varied between 150 g and 1000 g at most [34, 35]. The most commonly used mechanisms are those of exotendons and exoskeletons. The mechanisms of exotendons are characterized by the use of Bowden cables, which are put into guide paths to determine the resulting motion and range of motion [36]. In contrast, the exoskeleton is characterized by following a more structured mechanism, mainly activated by a linear actuator [37]. Among the most frequently used programs are SolidWorks [5, 27, 28], SketchUp [38], ADAMS [39], Blender, Meshmixer [38], Geomatic Freeform [35, 37, 40], and Vx Model [31], with SolidWorks being the most used (10% = 3 out of 30 papers). The Bowden cable-based design features three significant joints: the proximal interphalangeal joints (PIP), distal interphalangeal joints (DIPs), and metacarpophalangeal joints (MCPs) [5, 28, 41]. This design system is the most widely used (50% = 15 out of 30 papers) in which dimensions, ranges of motion, and anatomical relationships were taken into consideration.

Regarding the electronics system, among the most used microcontrollers is Arduino (30% = 9 of 30 papers). In five articles, Arduino Mega 2560 was used [27, 28, 42]; the rest are Arduino NANO [5, 31], Arduino UNO [29], Arduino MICRO [40], and Arduino Yún mini [43], operating at 5V; others are not very popular microcontrollers, such as the

Teensy 3.2 [44] and ESP32 (board manufactured by Espressif Systems) [38], which works at 3.3V. On the other hand, some prototypes are composed of Electromyography (EMG) sensors, for instance, MyoWare [24], FREEEMG 1000 wireless probes from BTS [45], and Myo armbands [43]. In addition, simple resistive force sensors, including the FSR-149NS [46], sensors with integrated gyroscopes (like the MPU6050, usually controlled by Arduino) [32], motion sensors similar to Kinect (manufactured by Microsoft) [28], or even pressure-force sensors [39], were mentioned. The location of these sensors is usually on the forearm because of the large signals that can be recorded and used to obtain patterns of gestures [46]. They also used devices responsible only for the direct control of the motors, for example, the DR8835 Motor Driver and the Acellus Panel (ASP-055-18) [34, 44]. Additionally, some of the systems reviewed use the following components: EHealth Shield for biometric readings [28], H-bridge modules to program DC motors, together with a PID controller [44, 47]. As a final point, in the power supply system, some authors used TIP3055 transistors, 1N4001 diodes, 100uF capacitors, and 5V LiPo batteries [38]. All electronic control and processing elements operate at 5 volts [44].

Regarding the informatic system, it is noteworthy that a significant 40% of these projects choose to use the Arduino IDE platform, along with its C++ programming language, for the development of hand orthoses [1]. There is a diversity of approaches and hardware configurations in the reviewed projects, with a noticeable use of Arduino in the majority of them [35, 40]. This usage ranges from the use of Arduino Mega, Nano, and Micro boards for programming to the implementation of various functionalities, thus allowing for efficient and flexible control of finger mechanisms. Additionally, the integration of electromyography (EMG) is evident in some projects, where Arduino is used to ensure its proper functioning [24, 27]. For example, the NuroSleeve glove, which incorporates EMG and integrates with Python-based software [31], and the Symbihand glove, an electrohydraulic hand orthosis controlled by EMG [47], are notable examples of this integration. Furthermore, other innovative research proposals have been found, such as the bilateral rehabilitation therapy implemented in the Bravo orthosis [48], which uses sensors and EMG in conjunction with Arduino for its operation [38, 49]. Furthermore, novel approaches are highlighted, such as virtual simulators, as in the case of the "PRISMA" prosthetic hand [41, 45, 50], whose CAD model was incorporated into the CoppeliaSim simulation environment and performed the desired gestures by the patient through the signals acquired from EMG sensors. Another simulation environment used was the Kinect for Windows SDK [28], where the 3D movement of the patient's arm was captured by a Kinect sensor, motivating them to perform virtual object grasps seen in the simulation. This virtual environment-based rehabilitation aims to alleviate patients' stress and make their recovery more enjoyable. Finally, the widespread use of Arduino offers an efficient and accessible solution for orthosis development, providing the necessary capacity and flexibility for independent control of servomotors, as well as access to a wide range of code libraries that facilitate the implementation of various functionalities.

1-5- Project Objective

After the analysis of the previously published studies, the authors identified a gap in the literature which is related to a clinical background explanation of stroke and types of rehabilitation, therefore, this study proposes a new technology for passive hand rehabilitation (detailed in Section 2) based on the introduction of a new mobile-prismatic joint mechanism. Although the Food and Drug Administration (FDA) classifies lower limb exoskeletons as a class II medical device, it is not defined for upper limb exoskeletons [51, 52]. On the other hand, the European Union utilizes the Medical Device Directive (MDD) 93/42/EEC, a directive primarily based on the International Organization for Standardization (ISO) ISO 13485 [53] standard, which classifies upper limb exoskeletons as class IIb devices. This classification is due to their active therapeutic nature, involving the exchange of energy with the human body in a potentially hazardous manner [54]. Similarly, the Canadian government categorizes exoskeletons as class II active devices, as they are therapeutic devices (including dedicated software) intended to administer or withdraw energy to or from the body [55].

Technology Readiness Levels (TRLs) are a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology [56]. So, according to TRL 3, a proof of concept model is proposed, because the main outcome indicators are: (i) data from experimental tests or analytical tests; and (ii) a demo or prototype for initial experimental tests. In addition, regarding the 2030 Agenda for Sustainable Development [57], this project mainly covers 4 goals: goal 3, “good health and well-being,” because of target 3.8: access to quality essential healthcare services. The goal 9 is “Industry, Innovation and Infrastructure” because of target 9.5: Enhance scientific research and upgrade the technological capabilities of industrial sectors in all countries, in particular developing countries [49]. The goal 10, “Reduced inequalities”, because of the target 10.2: Empower and promote the social, economic, and political inclusion of all, irrespective of age, sex, disability, race, ethnicity, origin, religion, or economic or other status. The goal 17, “Partnerships for the Goals”, because of target 17.8: fully operationalize the technology bank and science, technology, and innovation capacity-building mechanisms for least-developed countries by 2017 and enhance the use of enabling technology, in particular information and communications technology.

Therefore, the motivation of this study can be summarized in the proposal of a novel mechanism for motion transmission applied in each finger, and the introduction of a new robotic rehabilitation robotic device. The rest of the manuscript is structured as follows: In Section 2, materials and methods are described, and it introduces the methodology of the bio-design of the hand exoskeleton, including mechatronics design and simulation, as well as system manufacturing and integration. In Section 3, the test and results are shown, focusing on the motion of the system and the performance validation on humans. In Section 4, the paper ends with conclusions and further work.

2- Material and Methods

The research starts by defining the design methodology (based on VDI 2206 [58]) and gathering insights into passive hand wearable rehabilitation in post-stroke patients, including associated symptoms. Subsequently, the project underwent evaluation, taking into account clinical background, usability, and the imperative for a bioinspired design, in conjunction with the concurrent development of mechatronics (encompassing mechanical, electronic, and software domains) and meticulous material selection [59, 60]. This phase was pivotal in validating project objectives. Following this, specific requirements and project constraints were delineated. The conceptual design was anchored in the biomechanical principles governing hand function, with a preference for a rigid exoskeleton model [61]. Material selection was stratified into categories, including those for the exoskeleton, the circular-prismatic-joint remote center of motion (RCM) mechanism, and sensors for object detection. Computer-assisted design (CAD) analysis encompassed finite element analysis, consideration of anthropometric hand dimensions, and interference detection during assembly [62-64]. The development phase entailed the design of the mechatronic system, simulation, and additive manufacturing. Potential proof of concept applications were envisaged in rehabilitation centers and clinical settings (Figure 2).

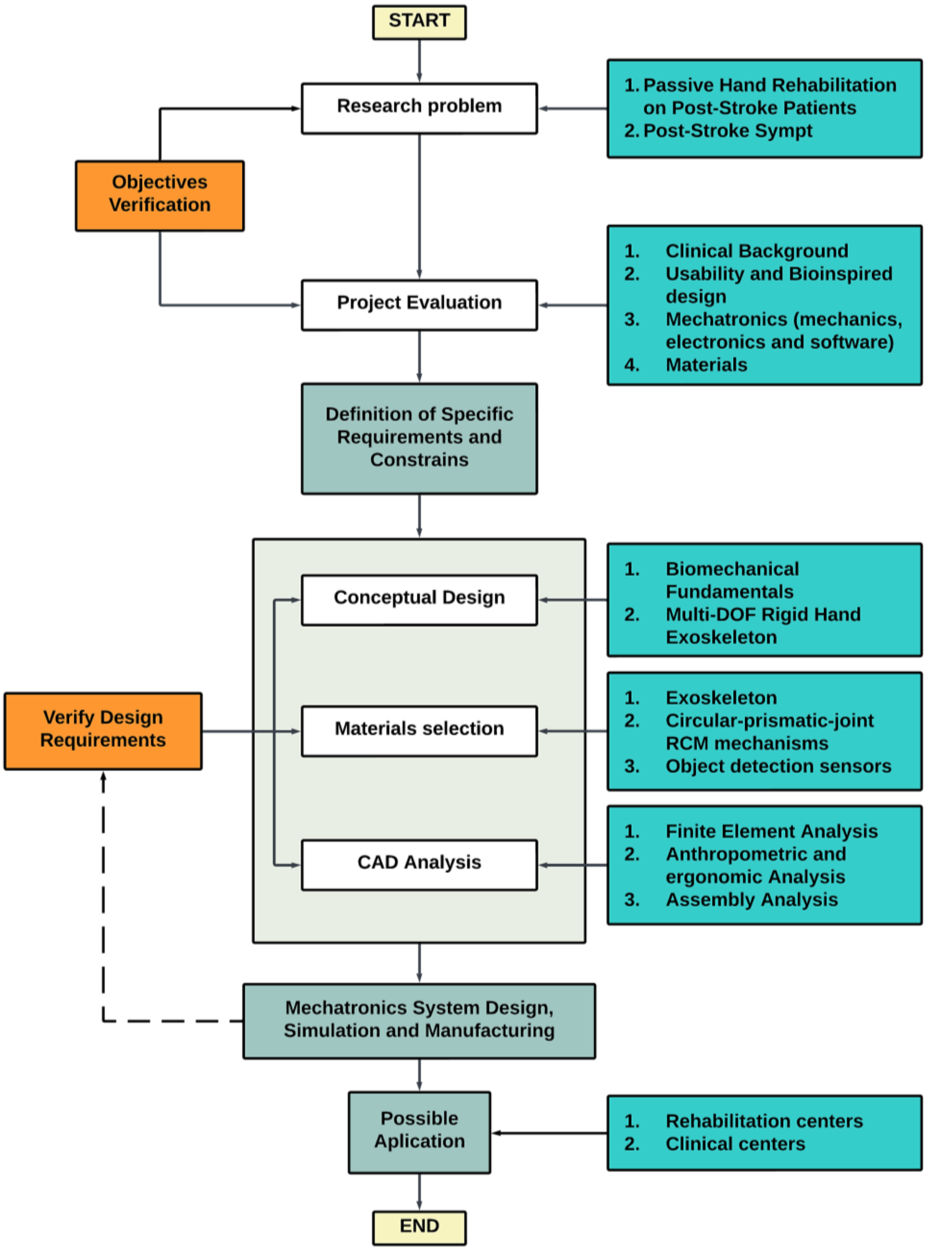

Figure 2. Bio-design Methodology of the hand exoskeleton

2-1- Mechatronics Design and Simulation

This research involves engineering fields such as mechanical, electrical, electronic, and computer science, which consist of using an exoskeleton with multiple degrees of freedom (DOF) to provide passive rehabilitation of the hand in patients who suffer from a cerebral vascular accident (CVA), also known as "stroke". The wearable exoskeleton has a system of prismatic-circular joint mechanisms driven by DS3218 Pro-180 20 kg-cm servomotors. In addition, RP-C7.6-LT pressure sensors (PS) are used so that they send a signal when they detect pressure on the fingertips.

2-2- a. Mechanics

After a rigorous analysis, it was determined that a design based on an exoskeleton is the most suitable choice for this project [65-67]. Its multiple advantages guarantee an ergonomic experience [68, 69]. Despite the lack of comfort or the risk of fracture of the mechanisms due to their small size, it was considered that the advantages outweigh the possible disadvantages. To improve the functionality and usefulness of the device in the biomechanical protocols and the grasping function, it was optimal to incorporate an extension at the tip of each finger, ensuring effective closure of the hand. The mechanical design was made using Fusion 360 software for its capacity to model prosthetics using free forms, which was the case with the back-of-hand cover. The metacarpophalangeal (MCP) mechanism is fixed to the cover to exert the motion by the actuator and to extend the linkages, while the radius of the MCP and distal interphalangeal (DIP) mechanism were restricted by the angular displacement of 60° to make a correct contraction of the hand. To adjust the system correctly to the fingers, velcro was considered in the rings (Figure 3).

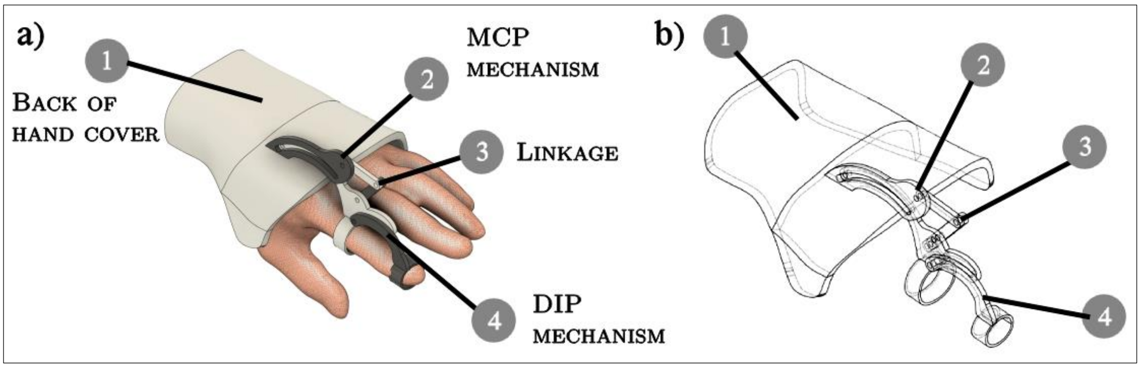

Figure 3. Exoskeleton design. a) Hatch view with edges. b) Layout view with hidden edges

2-3- a.1. Mechanical Design Considerations

Once the mechanism to be used was chosen, its limitations were taken into account. As it was an initial proof of concept phase, extension, and flexion were considered the only finger movements to be covered [70, 71]. The position where the fingers are initially located is parallel to the palm (extension). Based on these considerations, the exoskeleton-based mechanism was selected, which is the RCM with a mobile-prismatic joint that takes MCP and DIP as the centers, notated as VC1 and VC2 respectively. The system is supported on one end of the back-of-hand cover with a base of 20 mm. The mechanism flexes, exerting the necessary force to be capable of closing the fingers by a route of 60° and a horizontal displacement of 49.71 mm for the MCP mechanism and 27.57 mm for the DIP mechanism. Inversely, it extends to return the fingers to their initial position, as shown in Figure 4.

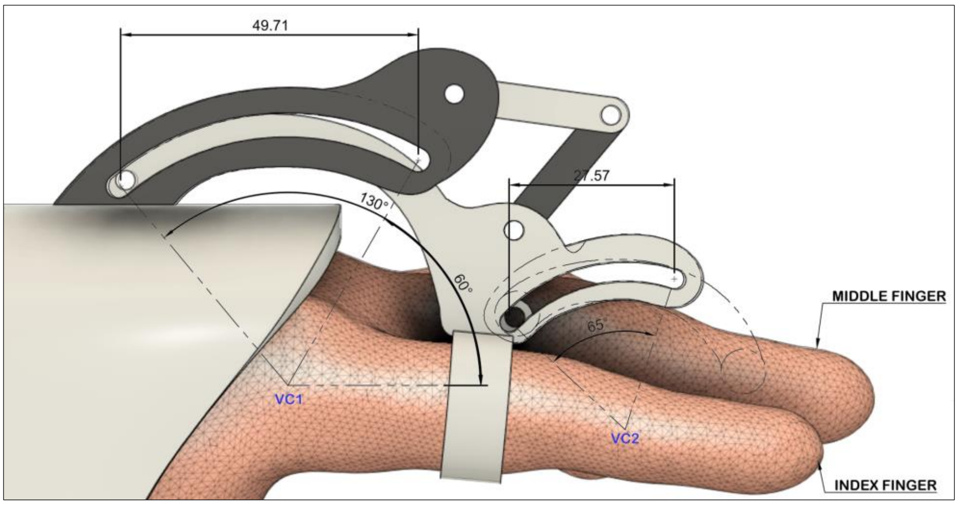

Figure 4. Proposed novel design of the mobile-prismatic jointed mechanism (Note that the measures are in mm)

For the actuator used, two options were considered: servomotors and micromotors [19, 72, 73]. The micromotor DC GA12-N20 has a reduction ratio gearbox and a high-power density, weighs around 10 g, has a rated torque of 2 kg × cm and a stall torque of 16 kg × cm, and a speed of 100 RPM at a rated voltage of 6 V, according to the motor's datasheet [74], occupies less space, and has a reduced weight. However, considering the grasping function, the torque is less than in the case of the servomotor DS3218, with a maximum of 20 kg-m, a mass of 60 g, and a working voltage of 5.0 ~ 6.5 V [75]. Although it has more weight, the servomotor was chosen because of its greater torque. Consequently, the transmission system considered was the connecting rod crank [76], using the servos as a crank and a developed connecting rod to exert force on the piston through a guide.

2-4-a.2. Ergonomic Motion Simulation

For the motion of the exoskeleton, initially, the fingers are parallel to the (1) back-of-hand cover; the RCM with a circular-prismatic joint mechanism is contracted through the (2) MCP mechanism until it reaches its maximum of 60°. The force is exerted by the servomotors pushing towards the (3) thumb ring and (4) the linkage mechanism for the rest of the fingers, and the (5) DIP mechanism is conducted to obtain a full contraction of the fingers. Inversely, the servomotors rotate to get the fingers to their initial position, as shown in Figure 5.

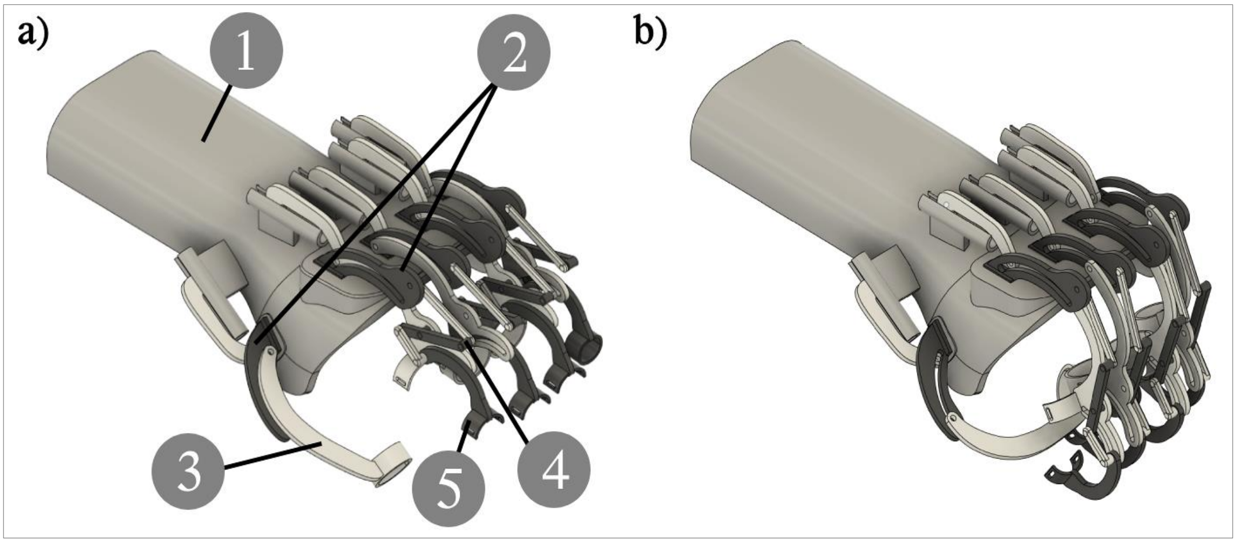

Figure 5. **a) Full extension of the fingers. b) Full contraction of the fingers**

For the mechanical design, actuators were considered to be placed in the (1) back-of-hand cover back part to exert force on the (2) back-of-hand cover front part through the (8) connecting rod crank system that actuates the (3) MCP mechanism for the (II) index, (III) middle, (IV) ring, and (V) little finger, as well as the (4) (I) thumb mechanism. Except for the thumb, the other mechanisms have (5) links that allow the extension and contraction of the finger by taking the (6) ring as the pivot point and being the virtual center. As a result, the (7) fingertip also follows the desired movement (Figure 6).

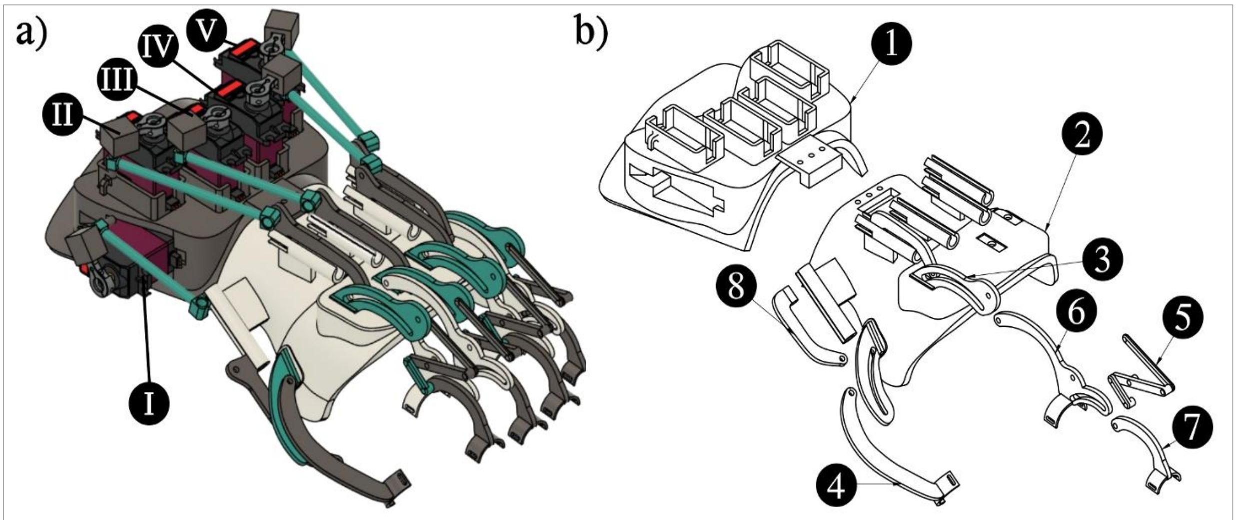

Figure 6. **3D design of the system: a) Complete system, b) Explosion view of the system**

2-5- a.3. Denavit-Hartenberg Analysis

In robotics (ROB), the Denavit-Hartenberg (D-H) algorithm is frequently used when series mechanisms are described [77]. With this description, calculation algorithms can be used to know the final positions of each link and joint. Each link is represented by the link length (ai) and the link twist (αi), which define the relative location of the two adjacent joint axes in space. Joints are also described by two parameters: the joint offset (di), which is the distance from one joint to the next along the axis of the link, and the angle of the joint (θi), which is the rotation of the joint concerning the next one around the axis of the link [7, 78]. In this way, the D-H parameters were obtained to model the kinematic chains for the fingers (Table 4), where they begin from the same wrist reference, and u1 and u2 indicate the distance from this axis to the thumb and the rest of the fingers, respectively. For the thumb, θt1, θt2, θt3 represent the active revolute joint, and Lt1, Lt2, and Lt3 are the distances between the joints, and the axis (X3, Y3, Z3) represents the tip of the thumb as the final actuator (Figure 7a). For the rest of the fingers, θf1, θf2, θf3, and θf4 represent the active mobile-revolute joint, Lf1, Lf2, Lf3, and Lf4 are the distances between the joints, and the axis (X4, Y4, Z4) represents the tip of the rest of the fingers as the final actuator (Figure 7b) [79].

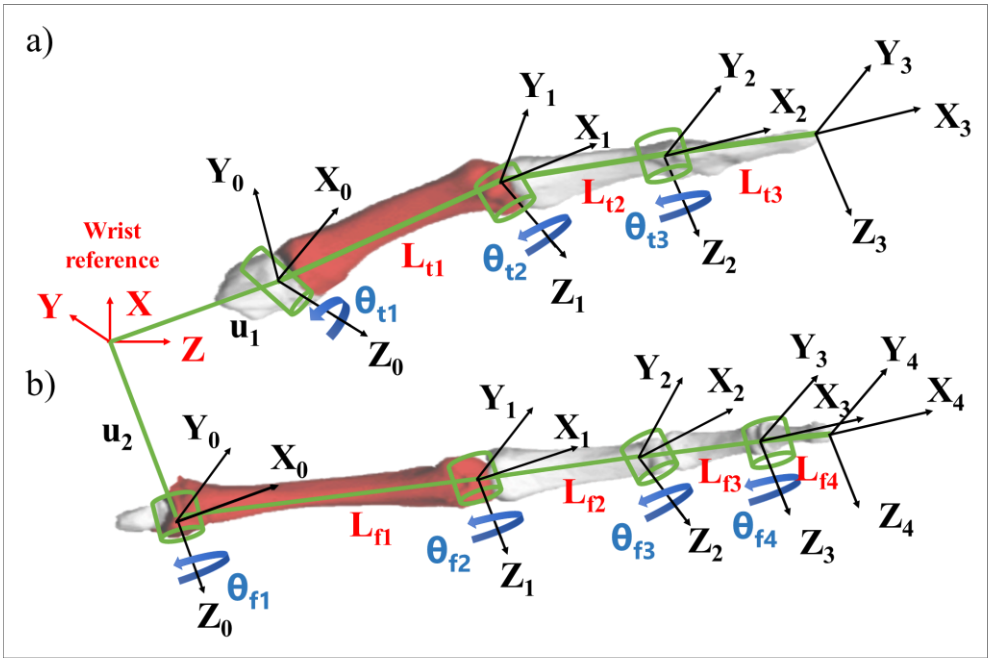

Figure 7. **DH parameters: a) Thumb kinematic chain, b) Kinematic chain for the rest of the fingers**

Table 4. **DH parameters for the fingers**

Link (i)	Thumb				Rest of the Fingers			
	θ_i	di	ai	αi	θ_i	di	ai	αi
1	θ_{t1}	0	L_{t1}	0°	θ_{f1}	0	L_{f1}	0°
2	θ_{t2}	0	L_{t2}	0°	θ_{f2}	0	L_{f2}	0°
3	θ_{t3}	0	L_{t3}	0°	θ_{f3}	0	L_{f3}	0°
4					θ_{f4}	0	L_{f4}	0°

2-6- b. Electronics

2-7- b.1. Control System

The board used is the Arduino Nano (Figure 8), which has the ATmega328 microcontroller clocked at a frequency of 16 MHz and 32 KB of flash memory for program storage, as well as 2 KB of RAM and 1 KB of EEPROM memory for non-volatile storage. In addition, it offers 14 digital input/output pins, 8 analog pins, and a mini-USB port. The programming language used is based on C++ in the Arduino IDE platform. The coded routines depend on sending a high or low signal through a group of typical non-locking push buttons, which controls the main menu scrolling function displayed on an LCD 16x2, using an I2C serial communication protocol by connecting an I2C LCD dedicated module driven by a PCF8574 integrated circuit and the selection function. This main menu allows the user to navigate with the scroll buttons and choose using the select button between 6 programmed servomotor routines. As an extra option, a function was used to restart the whole system using the "Reset Button" input pin from the Arduino Nano board to stop and restart the entire system to its original state [80].

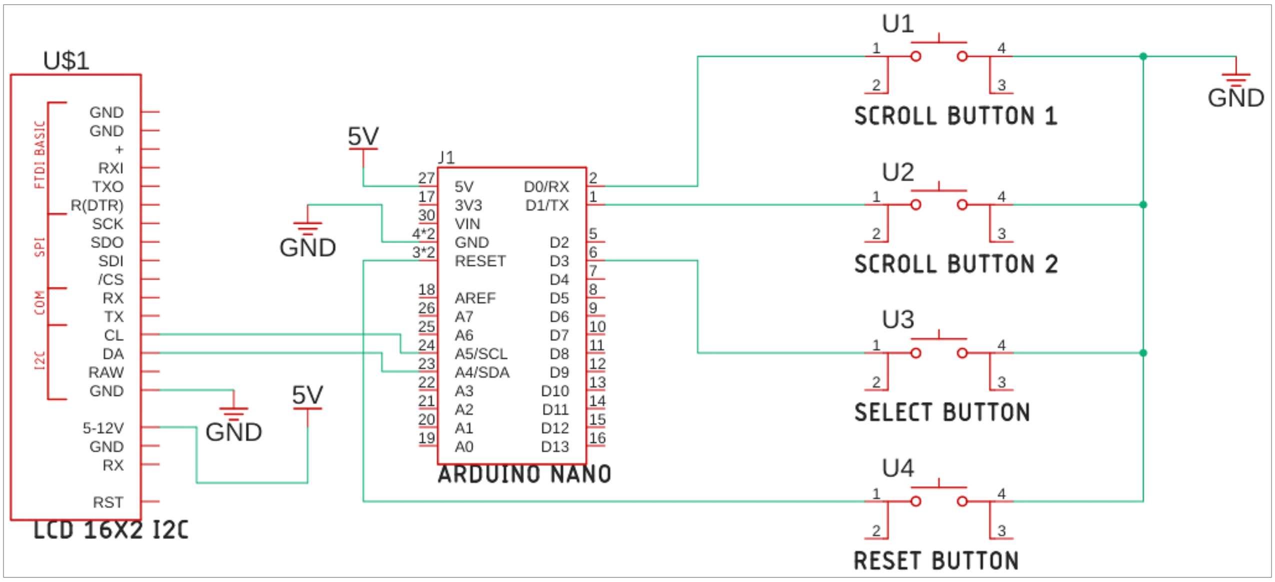

Figure 8. **Control System - Circuit Diagram**

2-8-b.2. Power supply and Feedback Circuit

Regarding the power supply for the system, it consists of an adjustable voltage source with a capacity of 6 amperes. The choice of this was based on the consideration of an extra safety margin of 20% (already surpassed by the power supply parameters), ensuring the power supply would have sufficient power for the operation of the exoskeleton. On the other hand, the feedback circuit (Figure 9) is composed of five RP-C7.6-LT (PS) with a round sensor of 7.6 mm in diameter and a pressure measuring range from 30 g to 1.5 kg. These are located on each finger and are responsible for sensing the force exerted when grasping an object in Protocol 6. Finally, as actuators, five DS3218MG servomotors were chosen, which can operate from 5V to 6.8V, exerting a torque from 19 kg-cm to 21.5 kg-cm, with a rotation range from 0° to 270°, where the servo's position is controlled by using PWM (pulse width modulation) from certain Arduino Nano board digital pins (the pulse width range for the servos goes from 500 to 2500 microseconds). This group of servomotors has the following incremental numerical finger distribution as considered previously (Figure 8): (I) thumb (SERVO 1), (II) index (SERVO 2), (III) middle (SERVO 3), (IV) ring (SERVO 4), and (V) little finger (SERVO 5).

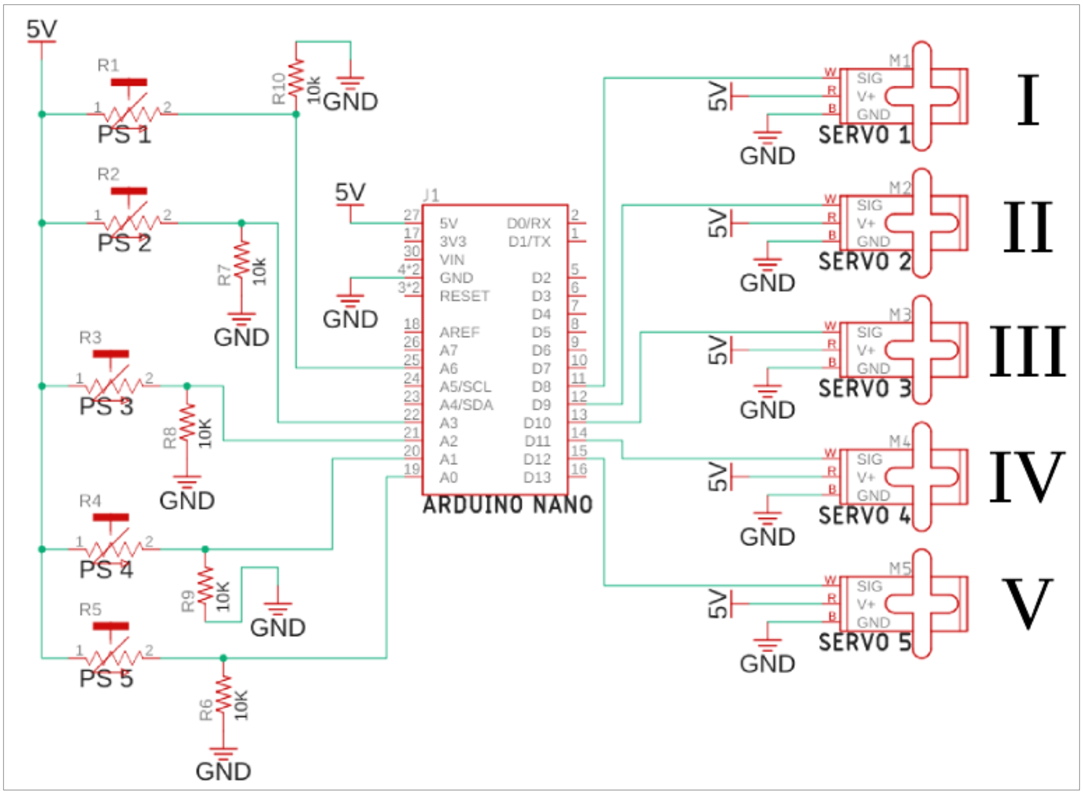

Figure 9. **Feedback circuit - Circuit Diagram**

2-9- System Manufacturing and Integration

2-10- a. Mechanical Prototyping

After the mechanical design, the model was exported from Fusion 360 software to STL binary to be used in the Flashforge program. A study shows that PLA has the highest tensile strength (33.7 MPa) using a layer thickness of 0.27 mm and an infill of 78% [81, 82], so to add more resistance, an infill of 100% was considered, supports were added, and the rest of the parameters were taken by default. For the pieces with curvature, it is recommended to print in the same direction as the extruder; this was the case for (1) supports, (2, 3, 4) linkages, and the MCP and DIP mechanisms as well, because of the holes for the nuts and bolts. The tolerances considered were 0.25 mm for mechanical connectors and 0.15 mm for 3D-printed pieces, resulting in a coupling without clearance. For parts that have the same geometry, such as (1) supports or (2, 3, 4) linkages, and are repeated in the design for each finger, it was preferred to use the mirror mode from Flashforge Creator 3 Pro rather than direct mode because it maximizes the time. Subsequently, the assembly for a finger was developed to check the operation of the mechanism, and then it was made for the (I) thumb, (II) index, (III) middle, (IV) ring, and (V) little finger considering the previous servomotor distribution (Figure 6a) as shown in Figure 10. Additionally, the development of the complete hand exoskeleton was made with a control station to access the menu and use the protocols previously defined, as shown in Figure 11.

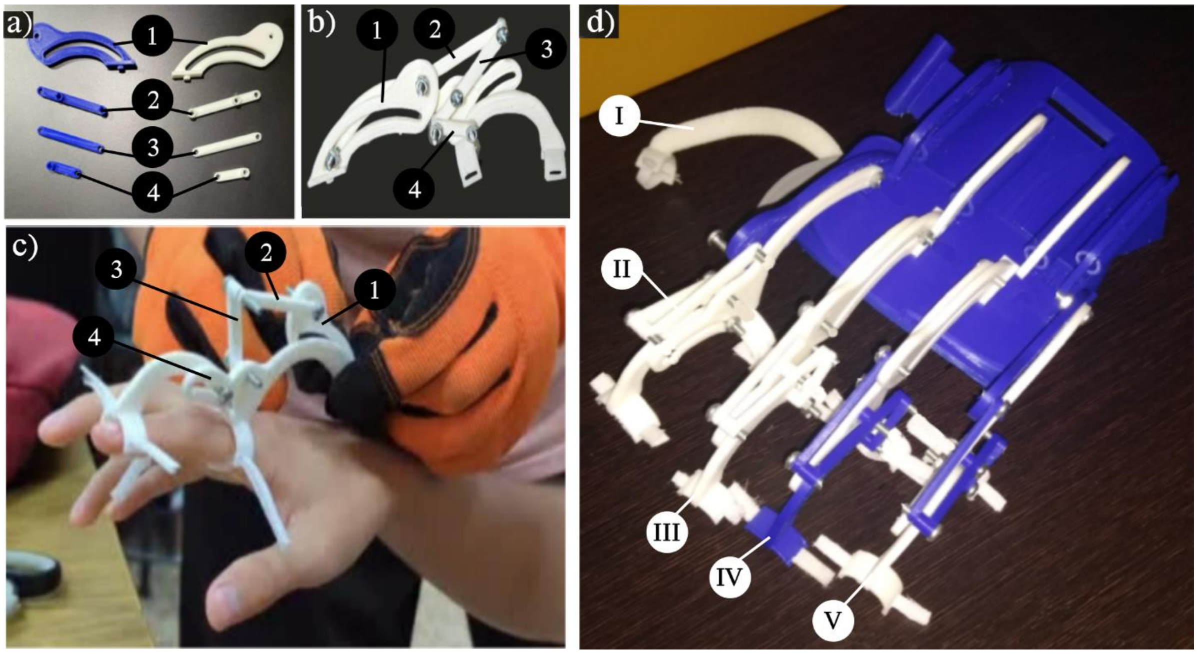

Figure 10. Mechanical prototyping phases: a) 3D-printed pieces, b) Assembly, c) Development of finger mechanisms, d) Partial exoskeleton Assembly

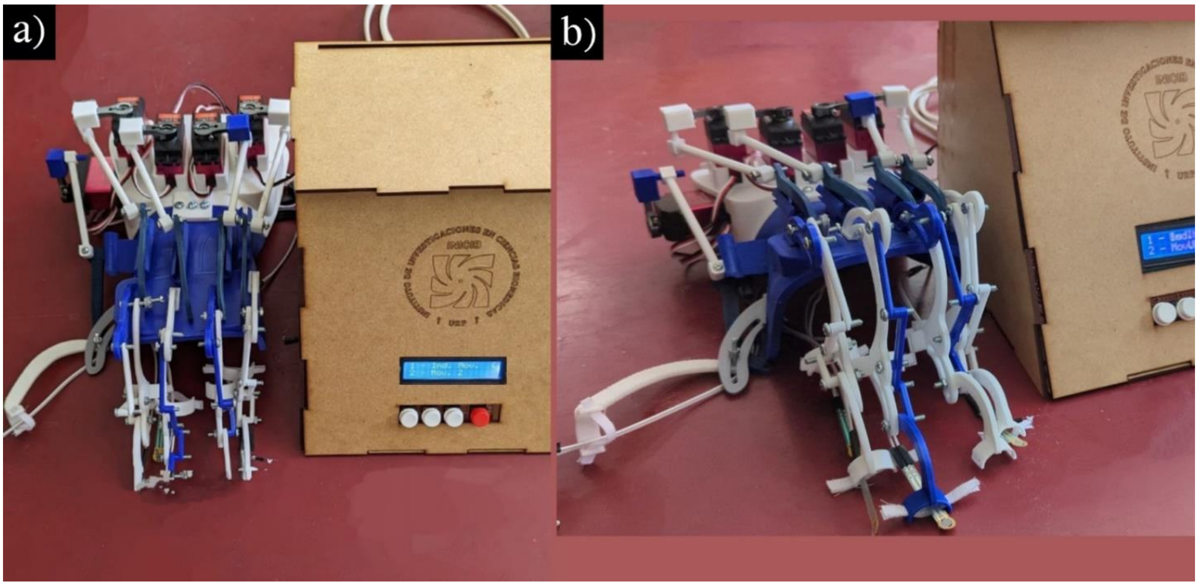

Figure 11. Preliminary design of the system: a) Front view, b) Isometric view

2-11- b. Electronics Prototyping

The development of the prototype consisted of testing the circuit on a solderless breadboard (16 x 5.4 cm) to get some measures, such as nominal current for particular components regarding the maximum amperage that the Atmega328 integrated circuit can normally handle (approximately 200 mA). Also, the maximum wattage delivered for the entire circuit toward the power supply (6.4 amperes roughly), in addition to real-time testing of the servomotor's programmed routines, the range of values of the PS to set a threshold for protocol 6, and some extra features such as the restart function, which can interrupt the activated sequence [83]. The following step after verifying the correct functionality of the circuit is to solder the following components: SERVO I, SERVO II, SERVO III, SERVO IV, SERVO V, as in the order of Figures 9 and 10, the buttons, display (Figure 12a), and the Arduino Nano (Figure 12b) on a single-sided perforated universal board to bring an improved presentation and firmness; thus, components do not come off easily in comparison with the previous breadboard mounting version. Furthermore, the welding was done using a standard 30-watt soldering iron in conjunction with a tin roll, which has a 60/40 size with a 0.8 mm diameter [84].

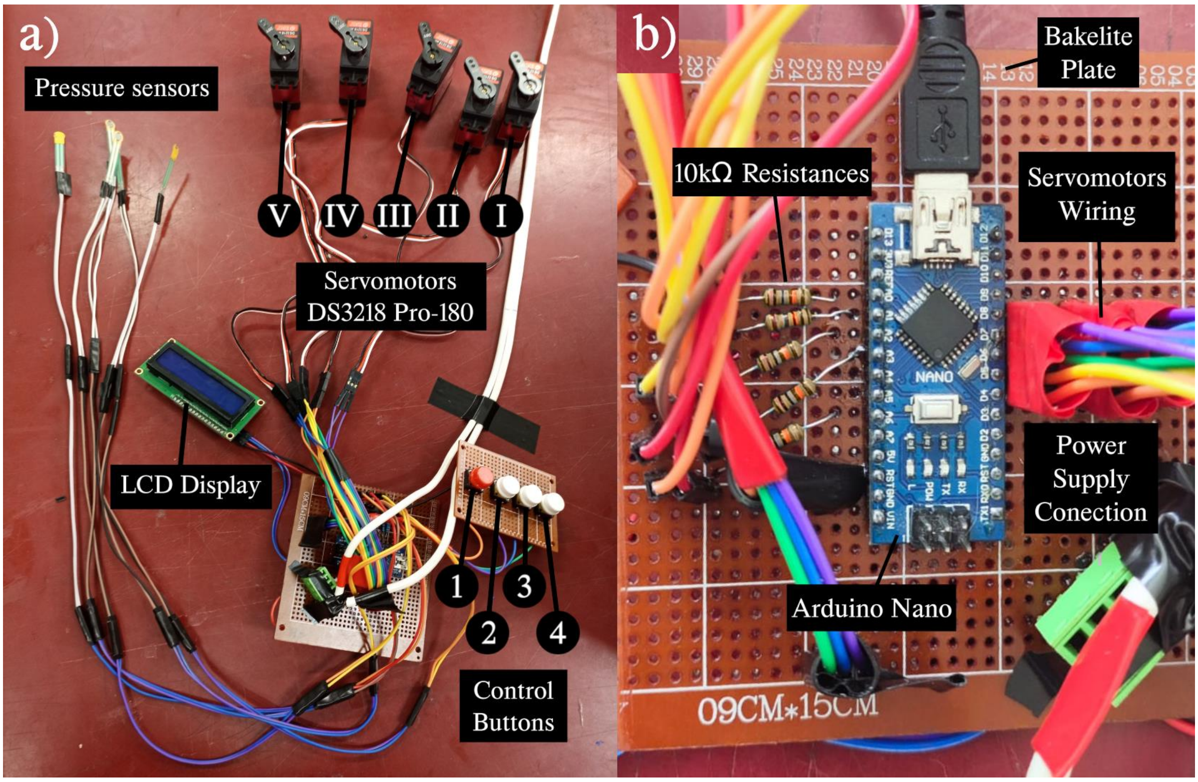

Figure 12. Final circuit welded to a bakelite plate: a) Full-circuit interconnected by a universal board, b) The main bakelite plate connects the control and feedback circuits to the power supply

2-12- c. Software Programming

It was decided to use the Arduino IDE 2.3.2 software to program the prototype components due to its significant advantages over previous versions, such as a more intuitive and user-friendly interface, improvements in stability and performance, as well as a straightforward way to search for and integrate the libraries required by the project.

This exoskeleton would require the use of libraries such as LiquidCrystal_I2C.h and Wire.h, which are crucial for their ability to simplify communication with the LCD screen using the I2C (Inter-Integrated Circuit) protocol. The LiquidCrystal_I2C.h library allows for simple and efficient control of the LCD screen, reducing the number of pins required for the connection. On the other hand, the Wire.h library is essential for I2C communication, facilitating data transfer between the Arduino and the I2C module. According to this, another essential library to use is VarSpeedServo.h for controlling the servo motors. This library allows for the use of up to 8 servo motors, optionally waiting (blocking) until the servo motor movement is complete, creating sequences of movements that run asynchronously, and setting a smooth movement speed for the servo motors, which is essential for the prototype in question. To support the correct movement of the servo motors, EEPROM.h library will be used, which allows to store the data that needs to persist through the restarts performed on the board. As shown in Appendix II - Table B, the code is organized into blocks starting with the libraries in use, the initialization of the screen and servo declarations, global definitions, local definitions, pin, and initial position definitions, the startup process, and presentation of the prototype on the LCD screen, the menu navigation process, the selection process of the required servo protocol, and the operation of the first and last protocol. The flow diagram that governs the prototype code is shown in Figure 13. The process that follows the code protocol starts with the integration of the aforementioned libraries. Furthermore, the control pins for the servomotors, the input pins for the PS, and the 4 buttons to be used are defined.

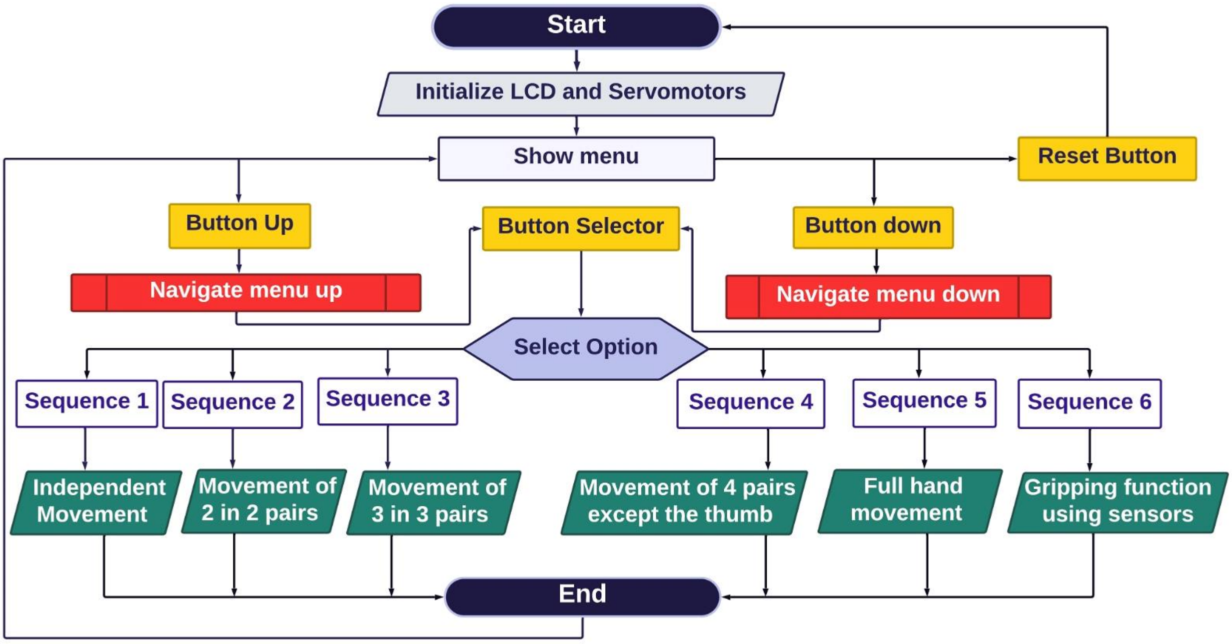

Figure 13. Code Flow Diagram

2-13- c.1. Options Menu and Buttons

After displaying a welcome presentation to the exoskeleton user, the LCD screen provides a menu in which the 6 displayed sequences can be navigated. Depending on the button presses, the menu variable is changed, determining which options are displayed on the LCD. The use of buttons for the selection of protocols is convenient for a simple and orderly execution. In this case, 3 buttons are used to navigate within the menu and select the desired option; these are configured as digital input with internal pull-up resistors using the digitalRead() function to read the state of the buttons and determine if they have been pressed. The up and down buttons (button_Up and button_Down) allow the user to scroll through the different menu options, increasing or decreasing the menu value. If the menu value reaches the maximum or minimum, it is reset to allow circular navigation. When the user presses the selection button (button_Select), an action is performed depending on the current menu option. This is achieved through a switch-case control structure, which executes a different code block depending on the menu value. For example, if the menu is equal to 0, the SeqServo_1() function is called, which performs a specific movement of the servos. In case any problems are detected or the sequence needs to be stopped due to an unforeseen circumstance, the fourth button (reset button) proceeds to interrupt the sequence, returning the servo motors to their initial position (putting the exoskeleton in the extended state) and causing the screen to display the welcome message, thus restarting the process.

2-14- c. 2. Sequence of Motions

The following functions are defined for sequences: (SeqServo_1(), SeqServo_2(), SeqServo_3(), SeqServo_4(), SeqServo_5(), SeqServo_6()) (as shown in Table 5) that control the movements of the servo motors according to different sequences; these according to what is specified in Section 1.1.b corresponding to the user protocols. These functions are called from the main loop (loop()) when the user selects a specific option from the menu:

Table 5. Functions for Evaluation Protocols

Functions	Explanation
SeqServo_1()	Controls the movements of each finger independently, except for the little finger, opening and closing each one sequentially. These movements go in order starting with the servomotor that flexes and extends the thumb, and the same for the index, middle, and ring fingers.
SeqServo_2()	Movements of 2 fingers are performed in 2 fingers, opening and closing each pair sequentially back and forth. These movements go in order starting with the servomotors that flex and extend the thumb and index fingers, the same for the index and middle pair, for the middle and ring pair, for the ring and little finger pair, and then repeating the movement in reverse until finishing with the thumb and index pair.
SeqServo_3()	Movements of 3 fingers are performed in 3 fingers, opening and closing them sequentially back and forth. These movements go in order starting with the servomotors that flex and extend the thumb, index, and middle fingers, the same for the index, middle, and ring, for middle, ring, and little finger, and then repeating the movement in reverse until finishing with the thumb, index, and middle.
SeqServo_4()	The movement of the 4 fingers excludes the thumb, opening and closing them. These movements constitute the flexion and extension of the little finger, ring, middle, and index fingers.
SeqServo_5()	Performs a closing and opening movement of the entire hand. This movement constitutes the flexion and extension of the 5 fingers.
SeqServo_6()	Function designed to control the gripping of objects by PS.

To control the movements of the servomotors, desired angles are set for each servo, and delays (delay()) are introduced to control the duration of each movement. In addition, to make use of the 6th object gripping sequence, pressure sensors and variables are used to store and manage the values recorded by the sensors. The logic used is based on the pressure measured by the PS, which gradually adjusts the angles of the servomotors, considering a minimum pressure on each servo while closing the hand to stop the movement.

3- Proof of Concept and Experimental Results

First, before the use of the exoskeleton system, a preliminary clinical assessment of the hand was conducted, considering both its functionality and anthropometric measurements using the mathematical formula related to the hand size shown in Equation 1 in the Section 1-1a of the manuscript. Regarding the mechanical design, angular displacement was restricted to 60° to achieve a complete closed-hand task (full flexion and extension) [85, 86] through the MCP and DIP mechanisms. Additionally, the force deployed by the crank and connecting rod system, facilitated by servomotors, was approximately 20 kg-cm, resulting in a displacement of 40 mm on each rail. The angular displacement of each finger is determined by the position of the servomotors; thus, the thumb, index, and little finger exhibit a displacement range of 87° to 127°, while the middle and ring fingers range from 87° to 47°. In the electronic and software programming domain, the Arduino Nano effectively managed system control, featuring a user-friendly interface displayed on an LCD screen for protocol selection among six available options. Lastly, the successful integration of the RP-C7.6-LT pressure sensor (PS) into the fingertips mitigated excessive pressure when grasping cylindrical objects.

The tests using the integrated exoskeleton system showed a maximum angle of 45° of flexion is reached (15% less than expected in the design and simulation), due to the different hand sizes, which causes a partial contraction of the fingers. Regarding the performance of the actuators, the servomotors exerted the anticipated torque (20 kg-cm) through the whole system, thus the middle finger performed the greater angular rotation, obtaining a displacement of 30 mm in the whole crank and connecting rod system and angular displacement of 40° from the initial position of 87°.

Second, the proof of concept test (Appendix III - Figure A) was carried out following motion protocols mentioned in Appendix IV - Figure B, on healthy adult persons (shown in Figure 14), at the Faculty of Engineering of the Ricardo Palma University. It began with a brief explanation of the manufacturing process, use of the exoskeleton, and biomedical theoretical explanation, then the product was placed on the subject's hand, and through a 6 protocol survey. The goal was to obtain enough number of affirmative responses related to the correct execution of each protocol to measure the subject's clinical satisfaction. Under Informed Consent (Appendix V – Figure C), the product was tested on 100 subjects (30% female and 70% male) with a mean age of 24.5 +/- 9.34 years. The mean success rate from protocol 01 to 05 was 91.6% (Figure 15). On the other hand, protocol 6 was tested on 91 subjects and the mean success rate was 63.7%. Regarding protocol P6, it was not tested on the 100 subjects because is planned to perform more tests to select a correct setpoint pressure to have a better grip and to change the angles increasing according to the force being applied rather than in 10° by 10° increments. In the case of protocol 6, the RP-C7.6-LT (PS) correctly sensed the pressure applied by the mechanical system while gripping a glass of water during the test, however, its integration with the other protocols was impractical. After the tests on each person, 25 out of 100 described feeling a greater force on the middle, ring, and little finger, in addition, the exoskeleton presented a better comfort in the male hands as opposed to the female hands, because of their smaller size. This research counts with the Ethical Approval Statement N° PI 008 2024 provided by the Institute of Research in Biomedical Sciences (INICIB) at Ricardo Palma University (Appendix VI – Figure D).

Figure 14. **Experimental Tests – Some Subjects**

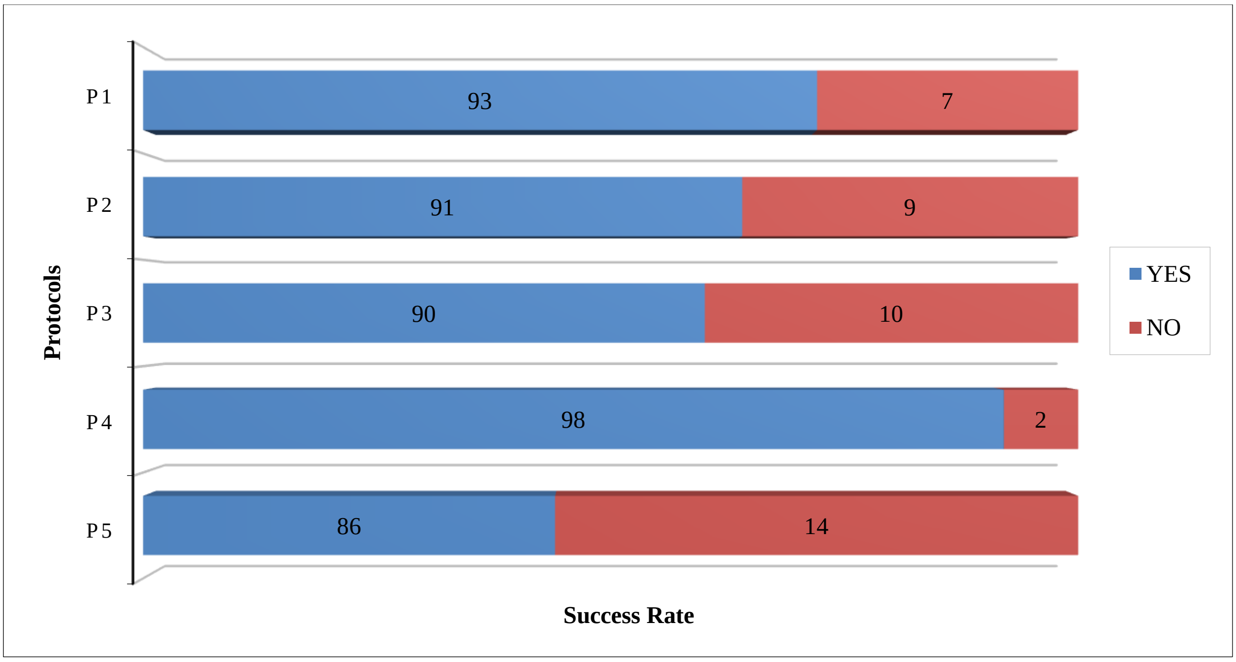

Figure 15. Success Rate Protocols (P1 to P5). Among the healthy subjects (100), the proof of concept using the hand-exoskeleton shows that P4 has the majority of acceptance (98%), while P5 has the minority acceptance (86%). It means that the project was completely successful because the main goal was achieved (finger flexion and extension); and now is ready to be optimized with the use of carbon fiber materials and electro-mechanical micromotors or electro-pneumatic valves in order to enhance the performance and increase the acceptance rate. This figure presents the results related to Appendix III.

Finally, the authors mention that the achieved results are in concordance with the information presented in the Section 1-2, having an important steppingstone related to the efficient motion of the fingers and improving the amplitude of rotative degrees, in addition, it presents a lightweight (510 g) structure which offers better wearable functionalities. Besides, the electromechanical actuators (servomotors) fit in the most used passive-type rehabilitation exoskeletons, but it is expected to replace them with soft actuation devices triggered by electro-pneumatic valves. Additionally, the mobile-prismatic joint mechanism is a pioneer, unique, innovative, and validated option that is ready to be tested on cerebrovascular accident (CVA) recovering patients.

4- Conclusion and Further Work

The present research addresses the growing need for innovative solutions in post-stroke hand wearable rehabilitation, which affects 15 million people. The design and development of a robotic exoskeleton for passive hand rehabilitation using a mechanism for the MCP and DIP with an angular displacement restriction of 60° is highlighted. The methodology used includes the use of Fusion 360 for the 3D design. For the selection of materials, PLA was chosen to print the mechanical prototyping as it has a high tensile strength (33.7 MPa) with a fill of 78%. For the actuators, DS3218 servomotors were used to exert a torque of 20 kg-cm, and RP-C7.6-LT pressure sensors with a maximum reading of 1.5 kg were used for the electronic implementation, adding a correct application of the programming software through the Arduino IDE. allowing the modification of the angles for the initial movement of each finger, starting from 87° and varying 40° per digit. Ergonomic simulation and Denavit-Hartenberg analysis will provide solid foundations for the design and development of the mechanism by knowing the kinematics of the fingers, guaranteeing the viability and effectiveness of the exoskeleton as a passive rehabilitation tool.

It is evidenced that the exoskeleton achieves the required standards for this first proof of concept, with the potential to be used in post-stroke hand rehabilitation. Thanks to the mechanism, the electronic integration, and the appropriate programming, it enables the execution of the suggested protocols. The prototypes were subjected to functional testing, confirming their promising potential for implementation in clinical rehabilitation settings. However, it was noted that the object grasping function only occasionally worked during testing due to pending adjustments in the code and mechanism. The future step of this project must include the acquisition of EMG signals and the use of linear actuators with micromotors to promote active hand rehabilitation, which could contribute to developing a full-arm rehabilitation system, with the goal of detecting incorrect muscle activation patterns, diagnosing muscle impairment, and evaluating treatment outcomes. Even it could be used for an astronaut's hand-muscle recovery during space flight [87, 88].

5- Abbreviations

AAN	Assistance As Needed	CAD	Computer Assisted Design
CVA	Cerebral Vascular Accident	DIP	Distal Interphalangeal
DOF	Degrees of Freedom	DLi	Length of each finger
D-H	Denavit-Hartenberg	EMG	Electromyography
FDA	Food and Drug Administration	HL	Hand Length
HW	Hand Width	IEEE	Institute of Electrical and Electronics Engineers
INICIB	Instituto de Investigación en Ciencias Biomédicas	ISO	International Organization for Standardization
I2C	Inter-Integrated Circuit	MCLi	Lengths of the metacarpals of each finger
MCP	Metacarpo phalangeal	MDD	Medical Device Directive
PL	Palmar Length	PLA	Polylactic Acid
PS	Pressure Sensors	PW	Palmar Width
RCM	Remote Center of Motion	ROB	Robotics
TIGER	Tenodesis Induced Grip Exoskeleton Robot	TLDi	Lengths for each digit
TRLs	Technology Readiness Levels	URP	Universidad Ricardo Palma
WC	Wrist Circumference	WHO	World Health Organization
WW	Wrist Width		

6- Declarations

6-1- Author Contributions

Conceptualization, M.V. and J.C.; data curation, M.V., J.C., J.M., B.O., V.C., A.N., D.A., L.G-V., G.T-M., M.R., R.R.M-G., Y.V., D.DLB., P.T.-Y., and S.C.; formal analysis, M.V., J.C., J.M., B.O., V.C., A.N., D.A., L.G-V., G.T-M., M.R., R.R.M-G., Y.V., D.DLB., P.T.-Y., and S.C.; investigation, M.V., J.C., J.M., B.O., V.C., A.N., D.A., L.G-V., G.T-M., M.R., R.R.M-G., Y.V., D.DLB., P.T.-Y., and S.C.; methodology, M.V., J.C., J.M., B.O., V.C., A.N., D.A., L.G-V., G.T-M., M.R., R.R.M-G., Y.V., D.DLB., P.T.-Y., and S.C.; project administration, M.V. and J.C.; resources, M.V. and J.C.; supervision, M.V. and J.C.; validation, M.V., J.C., J.C., R.P., and M.R.C.; visualization, M.V., J.C., J.M., B.O., V.C., A.N., D.A., L.G-V., G.T-M., M.R., R.R.M-G., Y.V., D.DLB., P.T.-Y., and S.C.; writing—original draft, M.V., J.C., J.M., B.O., V.C., A.N., D.A., L.G-V., G.T-M., M.R., R.R.M-G., Y.V., D.DLB., P.T.-Y., and S.C.; writing—review & editing, M.V., J.C., M.V.R., R.P., J.C., and J.A.DLC-V. All authors have read and agreed to the published version of the manuscript.

6-2- Data Availability Statement

The data presented in this study are available on request from the corresponding author. The project step shown in the manuscript has a copyright-exclusive license from the Institute of Research in Biomedical Sciences (INICIB), Dr. Mariela Vargas, and Dr. José Cornejo.

6-3- Funding

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6-4- Acknowledgements

Special thanks to the Institute of Electrical and Electronics Engineers (IEEE), and to the American Society of Mechanical Engineers (ASME).

6-5- Institutional Review Board Statement

The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board (or Ethics Committee) of the Faculty of Medicine at the Ricardo Palma University (protocol code PI 0082024 and date of approval: May 12th, 2024) for studies involving humans.

6-6- Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

6-7- Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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Appendix I

Table A. **Clinical considerations of hand exoskeletons for hand passive rehabilitation in post-stroke patients**

Article	Application	Summary
Effectiveness of Short-Term Robot-Assisted Rehabilitation in Patients with Hand Paralysis After Stroke: Randomized Controlled Trial [89].	Thirty-two patients, 34.4% of women with hand paralysis after a stroke.	Patients who used robot-assisted mobilization had a greater reduction in pain compared to the control group.
Clinical Test of a Wearable, High DOF, Spring Powered Hand Exoskeleton (HandSOME II) [90].	Twelve patients suffering from chronic stroke.	A significant increase was found in the range of motion and maximum extension angles.
HandMATE: Wearable Robotic Hand Exoskeleton and Integrated Android App for At Home Stroke Rehabilitation [91].	Five chronic stroke patients, middle age 45 years.	During a grip strength tracking task, errors using the HandMATE were minimal and comparable to an unassisted hand.
Internet of Things (IoT) Enables Robot-Assisted Therapy as a Home Program for Training Upper Limb Functions in Chronic Stroke: A Randomized Control Crossover Study [92].	Eighteen chronic stroke patients.	It was possible to train at home with TIGER, resulting in significant improvements in the block and box test (BBT) and range of motion (ROM) in the wrist joint.
Feasibility and potential effects of passive training of robot-assisted movement range in combination with conventional rehabilitation on hand function in patients with chronic cerebrovascular accident [93].	Twelve patients with chronic stroke were selected for the study.	After therapy, significant improvements were observed in the Fugl-Meyer evaluations, motor index, and functional independence mean. Its use is recommended as induction therapy before starting conventional therapy.
A comparison of the rehabilitation effectiveness of neuromuscular electrical stimulation robotic hand training and pure robotic hand training after stroke: A randomized controlled trial [94].	Thirty patients with chronic strokes.	Passive rehabilitation showed significant motor function recovery and a reduction in spasticity.
Testing of a 3D printed hand exoskeleton for an individual with stroke: a case study [95].	An individual patient.	Improvements were found in the Fugl Meyer assessment scores, assisting the participant during functional hand assessments.
Robot-Assisted Rehabilitation of Hand Paralysis After Stroke Reduces Wrist Edema and Pain: A Prospective Clinical Trial [96].	Thirty-five participants aged 45 to 80 years, with functional impairments of their upper extremities after a stroke.	Through the evaluations, a significant decrease in edema was obtained by 5.4% and pain on VAS scales.

Appendix II

Table B. Robotic Exoskeleton Programming – Partial Code

LIBRARIES	**#include <LiquidCrystal_I2C.h>**	**#include <Wire.h>**	**#include <VarSpeedServo.h>** **#include <EEPROM.h>**
STARTUP AND SERVO DECLARATION	LiquidCrystal_I2C lcd(0x27, 16, 2); VarSpeedServo servo1; VarSpeedServo servo2;	VarSpeedServo servo3; VarSpeedServo servo4; VarSpeedServo servo5;	
GLOBAL DEFINITIONS	#define Servo1_pin 4 #define Servo2_pin 5 #define Servo3_pin 6	#define Servo4_pin 7 #define Servo5_pin 8 #define button_Up 0	#define button_Down 1 #define button_Select 12
LOCAL DEFINITIONS	int PS1 = A0; int PS2 = A1; int PS3 = A2; int PS4 = A3; int PS5 = A7; *// The LCD I2C uses A4 and A5*	int constant1 = 50; int constant2 = 130; int menu = 0; int speed_servo = 20; int delay_a = 2000; int delay_b = 3000;	const int setpoint_pressure = 500; int init_angle = 85; int eeprom_speed = 0; int init_speed = 20; int ang_min = 0; *int Pos1 = 87;* *int Pos2 = 86;*
PIN DEFINITIONS AND INITIAL POSITIONS	void setup() { EEPROM.write(0, init_angle); ang_min = EEPROM.read(0); EEPROM.write(1, init_speed); eeprom_speed = EEPROM.read(1); pinMode(button_Up, INPUT_PULLUP); pinMode(button_Down, INPUT_PULLUP); pinMode(button_Select, INPUT_PULLUP); pinMode(PS1, INPUT); pinMode(PS2, INPUT);	pinMode(PS3, INPUT); pinMode(PS4, INPUT); pinMode(PS5, INPUT); servo1.attach(Servo1_pin); servo2.attach(Servo2_pin); servo3.attach(Servo3_pin); servo4.attach(Servo4_pin); servo5.attach(Servo5_pin); delay(2500);	servo1.slowmove(ang_min, eeprom_speed); servo2.slowmove(ang_min, eeprom_speed); servo3.slowmove(ang_min, eeprom_speed); servo4.slowmove(ang_min, eeprom_speed); servo5.slowmove(ang_min, eeprom_speed);
PRESENTATION OF THE LCD SCREEN	lcd.init(); lcd.backlight(); String msg1 = " Exoskeleton "; String msg2 = " by INICIB URP "; for (int lcd_width1 = 16; lcd_width1 > 0; lcd_width1--) {	lcd.setCursor(lcd_width1,0); lcd.print(msg1); lcd.setCursor(lcd_width1,1); lcd.print(msg2); delay(250); } delay(2000); } *// End of the function setup*	

SELECTING THE REQUIRED SERVO SEQUENCE	if (digitalRead(button_Select) == LOW){ switch (menu) { case 0: *//Option selected 1* SeqServo_1(); break; case 1: *//Option selected 2* SeqServo_2(); break; case 2: *//Option selected 3* SeqServo_3();	break; case 3: *//Option selected 4* SeqServo_4(); break; case 4: *//Option selected 5* SeqServo_5(); break; case 5: *//Option selected 6* SeqServo_6(); break;	} } delay(50); *//Delay to prevent false button readings* } *// End of the function Loop*
FUNCTION OF THE FIRST PROTOCOL	void SeqServo_1() { //Independent finger movement lcd.clear(); String msg5 = " Protocol 1 "; String msg6 = " In Progress..."; lcd.setCursor(0,0); lcd.print(msg5); lcd.setCursor(0,1); lcd.print(msg6); //Thumb servo1.write(constant1,speed_servo,true); delay(delay_a); servo1.write(87,speed_servo,true); delay(delay_b);	//Index servo2.write(constant2,speed_servo,true); delay(delay_a); servo2.write(87,speed_servo,true); delay(delay_b); //Middle finger servo3.write(constant2,speed_servo,true); delay(delay_a); servo3.write(87,speed_servo,true); delay(delay_b);	//Ring finger servo4.write(constant1,speed_servo,true); delay(delay_a); servo4.write(87,speed_servo,true); delay(delay_b); }
FUNCTION OF THE SIXTH PROTOCOL	void SeqServo_6() { lcd.clear(); String msg5 = " Holding Object "; String msg6 = " In Progress..."; String msg7 = " Completed "; lcd.setCursor(0,0); lcd.print(msg5); lcd.setCursor(0,1); lcd.print(msg6); delay(2000); int PSProm = (analogRead(PS1)+analogRead(PS2)+analogRead(PS3)+analogRead(PS4) +analogRead(PS5))/5;	while (PSProm < setpoint_pressure && Pos1 > 50) { Pos1--; servo1.write(Pos1, 10); servo4.write(Pos1, 10); servo5.write(Pos1, 10); if (Pos2 < 130) { Pos2++; servo2.write(Pos2, 10); servo3.write(Pos2, 10); } PSProm = (analogRead(PS1)+analogRead(PS2)+analogRead(PS3)+ analogRead(PS4)+analogRead(PS5))/5; delay(15); }	servo1.write(Pos1, 10); servo2.write(Pos2, 10); servo3.write(Pos2, 10); servo4.write(Pos1, 10); servo5.write(Pos1, 10); lcd.clear(); lcd.setCursor(0,0); lcd.print(msg5); lcd.setCursor(0,1); lcd.print(msg7); delay(60000); servo1.write(85,10,false); servo2.write(85,10,false); servo3.write(85,10,false); servo4.write(85,10,false); servo5.write(85,10,true); }

Appendix III

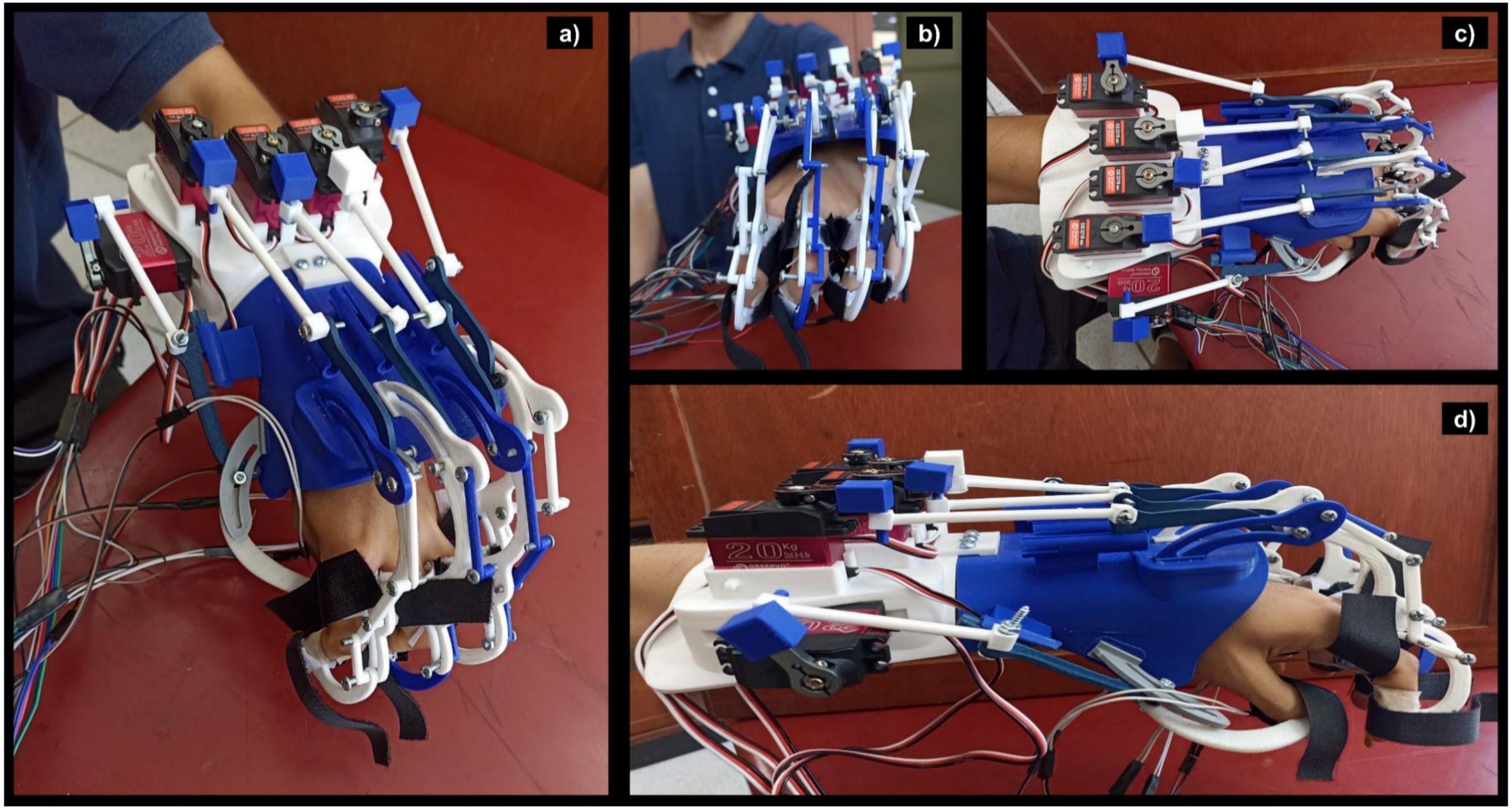


Figure A. **Hand Exoskeleton Test – Views: a) Isometric, b) Front, c) Top, d) Right side**

Appendix IV

PROTOCOL

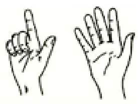
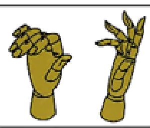
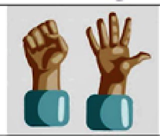
INSTRUCTIONS:

The data collection sheet you have in your hands is part of an investigation. Your participation in this study is voluntary, by completing the survey we understand that you provide your consent to participate in the study. The data provided is confidential and anonymous. The results of this study will be published in a scientific journal. Answer the marking questions with "X".

March 2024

GENERAL DATA

Sex: Male ( ) Female ( ) **Age:** ________years old

EVALUATION PROTOCOLS		ACHIEVED?	
		YES	NO
P1. Perform the flexion and extension movement of each finger independently from the index to the ring finger. Note: The little finger cannot make independent flexion movement, since it is anatomically united with the ring finger.			
P2. Perform the 2-finger flexion and extension movement on 2 fingers: o First: the thumb + the index finger o Second: the middle finger + the ring finger o Third: the ring finger + the little finger o Finally: back to the thumb.			
P3. Perform the 3-finger flexion and extension movement on 3 fingers: o First: the thumb + index finger + middle finger o Second: the index finger + the middle finger + the ring finger o Third: the middle finger + ring finger + little finger o Finally: back to the thumb.			
P4. Perform the flexion and extension movement of 4 fingers: index finger + middle finger + ring finger + little finger			
P5. Perform the flexion and extension movement of the 05 fingers: closing and opening the fist.			
P6. Hold an object (canned drink) with your hand.			

Thanks.

Figure B. Experimental Test Motion Protocol – Form. It covers 6 protocols, from P1 to P6

Appendix V

INFORMED CONSENT

This research is conducted by Mariela Vargas et al., and managed by the Ricardo Palma University. The objective of this study is to design and test a prototype of a hand exoskeleton for passive rehabilitation.

If you agree to participate in this study, you will be asked to try out the hand-exoskeleton prototype and answer a few brief questions. This will take approximately 10 minutes of your time. Participation in this study is strictly voluntary. The information collected will be confidential and will not be used for any purpose other than this research. Your responses to the questionnaire and interview will be coded using an identification number and will therefore be anonymous.

If you have any questions about this project, you can ask questions at any time during your participation in it. Likewise, you can withdraw from the project at any time without harming yourself in any way. If any of the questions during the interview seem uncomfortable to you, you have the right to let the researcher know or not answer them.

Testing the prototype will not generate pain or anticipated injury. However, being a prototype, it is not exempt from any possible error in the execution of the test such as: a possible breakage of a mechanical part; however, it has emergency sensors that will stop any operation.

Thank you in advance for your participation.

Accept : ( )
Not Accept : ( )

Figure C. Informed Consent – Form

Appendix VI

COMITE DE ETICA EN INVESTIGACION
FACULTAD DE MEDICINA "MANUEL HUAMAN GUERRERO"
UNIVERSIDAD RICARDO PALMA

CONSTANCIA

La presidenta del Comité de Ética en Investigación de la Facultad de Medicina de la Universidad Ricardo Palma deja constancia de que el proyecto de investigación:

Título: **MECHATRONICS BIO-DESIGN AND DEVELOPMENT OF ROBOTIC EXOSKELETON SYSTEM WITH MOBILE-PRISMATIC JOINT MECHANISM FOR PASSIVE HAND WEARABLE-REHABILITATION**

Investigadores: **MARIELA VARGAS, JOSE MAYORGA, BERNABÉ OSCCO, VICTOR CUYOTUPAC, ADRIAN NACARINO, DAVID ALLCCA, LUIS GAMARRA-VÁSQUEZ , GABRIEL TEJADA-MARROQUIN, MATHIAS REATEGUI, RENZO R. MALDONADO-GÓMEZ, YUDDY VASQUEZ, DAIRA DE LA BARRA, PAMELA TAPIA-YANAYACO, SANDRA CHARAPAQUI, MILTON V. RIVERA, RICARDO PALOMARES, MABEL RAMIREZ-CHIPANA, JORGE CORNEJO, JOSÉ CORNEJO, JHONY A. DE LA CRUZ-VARGAS.**

Código del Comité: **PI 008 2024**

Ha sido revisado y evaluado por los miembros del Comité que presido, concluyendo que le corresponde la categoría revisión expedita por el periodo de un año.

Exhortamos a la publicación del trabajo de investigación, con el fin de contribuir con el desarrollo científico del país.

Lima, 12 de mayo de 2024

Dra. Consuelo del Rocío Luna Muñoz
Presidenta del Comité de Ética en Investigación

Figure D. Ethical Approval Statement N° PI 008 2024 (written in Spanish, the official language of Peru)