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Original Article

Development of an Exoskeletal Glove using Hybrid Robotics for Motor Function Rehabilitation

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Abstract - *The number of people with motor disabilities has increased compared to previous years, and it is estimated that it will continue to grow; the fact that a part of the body does not function properly limits the independence of the affected person, an important part is a hand because with it we interact with our environment. To recover its functionality, therapeutic exercises are usually performed; from engineering, one of the proposals is the use of an exoskeleton. Many exoskeletons apply rigid or soft robotics, and very few are hybrids. Therefore, in this work, a hybrid exoskeleton glove is developed to detect the user's intention of movement; for this purpose, a resistive force sensor was used. For the movement, servomotors with a crank-crank mechanism were used to obtain a linear movement. The tests consisted of a force measurement and the adaptability of the device when holding different objects. Relatively low weight was obtained, and considering the number of actuators, the force achieved is efficient for performing Activities of Daily Living (ADL).*

Keywords - *Exoskeletal glove, Hybrid robotics, Arduino, Hand Rehabilitation, Movement intention.*

1. Introduction

Approximately one billion individuals, accounting for 15% of the global population, are living with some form of disability. This number is projected to increase significantly in response to current demographic trends and the prevalence of chronic illnesses. Consequently, it is anticipated that nearly everyone will encounter some form of disability at some point in their lives. According to the World Health Organization (WHO), approximately 1.71 billion people across the globe are affected by musculoskeletal disorders, making them the leading cause of disability worldwide. Furthermore, it is estimated that annually, between 250,000 and 500,000 individuals suffer from spinal cord injuries, resulting in disability for a significant portion of those affected. [1].

According to the Pan American Health Organization (PAHO), there are approximately 85 million people with disabilities in Latin America due to the demographic changes of the current population, and it is also mentioned that cardiovascular diseases could cause more deaths and disabilities than infections during the first decades of the 21st century [2]. In the United States, the majority of people who have suffered strokes (6.6 million) and traumatic brain injuries (5.3 million) have had their hand function affected [3]. In addition, annual figures indicate that 12,500 people survive spinal cord injuries, so many of them will have some type of disability [4].

As for Peru, data from the National Institute of Statistics and Informatics (INEI) show that 1.575 million people have some kind of disability, of which 59.2% (932 thousand people) have motor disabilities [5-7]. According to the National Council for the Integration of People with Disabilities (CONADIS), in 2019 and 2020 alone, 18.64% (57,499 people) were registered in the National Registry of People with Disabilities (RNPCD) since 2000 of the total number of registered people, 29,505 people have a musculoskeletal impairment; a comparison with previous years shows an increasing trend in the number of disabled people [8]. Nowadays, many strokes generate movement problems in the hands; this problem could need an exoskeleton with a control system based on movement intention to be solved. In [9] a study on motion intention detection is developed; for this purpose, a control system that can detect with good performance the hand motion intention is elaborated. The system was tested in experiments on 8 patients with cerebrovascular lesions with a wide range of severity; the results obtained by the sensors were analyzed with different methods. Accurate detection of movement intentions was achieved in most of the tests performed on the participating patients. There were a few cases (the most severe) where this proposed system was not effective. This work proposes that having electromyographic (EMG) readings and a motion intention detection control system using pattern recognition allows better detection accuracy, which is effective to a certain extent, since in patients with more severe lesions, the system does not work effectively. Like stroke, spinal cord injuries can also lead to loss of strength in hand movements. In [10], an exoskeleton is created to restore hand function in people with the aforementioned injuries. To test the device, the participants of the experiment held three objects with different shapes: box, cylinder and sphere. For data acquisition, a platform was used with a receiver at the bottom of the platform attached to test objects at the top. The participants had to lift each object, and the receiver recorded the force applied; this was done three times for each object with and without the exoskeleton. At the end of the tests, very good results were obtained, as the gripping force with the exoskeleton on was greatly increased with respect to the force exerted without the exoskeleton. On the other hand, as the area of the object increased, the difference in force between the index and middle finger also increased. Although the presented exoskeleton fulfills its purpose, it does not consider all the fingers of the hand that could influence a better grip; moreover, the drive system has a weight that restricts portability somewhat.

Something important to take into consideration when designing exoskeletons is that the device should be adapted to be used by people with different degrees of hand stiffness after a stroke. Therefore, in [11], an exoskeletal glove is created with variable, flexible parts that adapt to the hand size of each patient and to the rehabilitation exercises to be performed. To build each finger, 3D printed molds were used, which are attached to the glove with Velcro, and two tests were performed; one regarded the range of motion by measuring opening angles and the grip strength by pressure sensors. This prototype robotic glove recorded ranges of motion similar to those performed by a healthy hand and higher grip strength. This study raises an interesting feature, which is the variable flexibility of the robotic glove to be adjustable to the shape and size of the hand; however, each finger to be customized for the tasks to be performed has to be elaborated, which is tedious.

In the design of exoskeletons, there are options with rigid or soft robotics; there are few designs that explore this rigid-soft spectrum; because of this, people with motor deficiencies in the hand may not have an adequate device to perform daily activities and at the same time rehabilitate. In [3], a hybrid exoskeletal glove (rigid-soft) is designed and tested to assist in performing Activities of Daily Living (ADL) and motor recovery exercises. For this purpose, a glove with soft parts and rigid parts was developed, taking advantage of both approaches. A test was performed on a person with vertebral damage, and he mentioned that the exoskeleton should have more rigid parts and be suitable for heavier lifting exercises. To quantify the data, sensors were used to measure grip strength and ranges of motion; both the ranges of motion and grip strength of the device exceeded the values set at the beginning of the investigation.

This study presented an unusual approach in exoskeletons, which is a hybridization between rigid and soft elements, which adds advantages of both types; however, the proposed design has aspects of improving, among them, the total weight of the system.

People who have partially lost motor function in their hands often require intensive rehabilitation using an optimally functioning exoskeleton. In [12], a hand exoskeleton controlled by EMG signal readings is designed and tested. The exoskeleton design includes 3D printed parts, linear actuators, and a surface EMG signal reader. Experiments were carried out to find out the motion ranges and reliability when using EMG intention detection. As a result, large ranges of motion were obtained for the joints in the exoskeleton, and the effectiveness of the use of two actuators to naturally control the movement of the thumb was also shown; additionally, it was obtained that the detection of surface EMG signals proved to be very accurate. This exoskeleton presents large ranges of motion, in addition to proving that using two actuators for the thumb can achieve a movement similar to that of a healthy thumb; however, in the absence of strength tests, it is not known if it really serves for activities of daily living, in addition to the proposed design does not meet the characteristic of low complexity and compactness.

One way to optimize an exoskeleton is by making it capable of being activated by the user's intention since this kind of device is required for the rehabilitation of muscles that are losing mass when they are not used. In that sense, in [13], a hybrid exoskeleton is built to enable rehabilitation using electroencephalographic (EEG) readings to control the exoskeleton with the user's attention. To this end, a simple, low-weight hybrid robotic glove was developed that is activated by attention provided by the patient while using a graphical interface. The attention-based control proved to be very efficient. The strength and ranges of motion obtained with this device are acceptable for performing activities of daily living. The proposed robotic glove optimizes certain aspects of other design approaches; also, the attention-based control gave good results; however, the ranges of motion and grip strength could be optimized; also, the use of EEG detectors makes the price of the system increase considerably.

One aspect that is required in robotic handheld exoskeletons is that they should be lightweight and compact for continuous use in ADL while aiding in rehabilitation. For such a reason, in [14], a lightweight EMG-controlled exoskeleton is modified for improved grasping. The modified exoskeleton was the Tenoexo, and improvements were made to allow abduction/adduction movements and improve grip strength. To reduce weight, 3D printing was applied. The tests were carried out with the aid of an extra circuit involving one healthy subject and two subjects with vertebral lesions. According to the data obtained, improvements were recorded in the grip strength of the device with respect to the original;

additionally, good ranges of motion and a relatively low weight were obtained. In this exoskeleton, the grip strength of an existing model was increased. It also has a structure that allows a more natural movement of the thumb, and despite having increased the weight compared to the original, this increase is not very large; on the other hand, the grip strength achieved is still low compared to other devices, as well as the ranges of motion.

To detect the movement intention of patients wearing exoskeletons, it is common to use EEG or EMG sensors or both. However, force sensors could be used, which are cheaper. Thus, in [15], an exoskeleton that detects motion intention using force-sensing resistors is designed and tested. For the structure of the exoskeleton, 3D parts were printed so that modules can assemble it; the electronic part is composed of pressure sensors on the fingers that send data to the control system (Arduino), and the latter activates linear actuators for flexion and extension of wires attached to the fingers. The experimental part was conducted with 10 healthy participants where forces were measured without the use of the exoskeleton, with the exoskeleton turned off and then turned on. It was noted that simply using the exoskeleton without the need for it to be energized increased the grip and pinch forces in the participants and, when turned on, further increased the force in the hand, implying a decrease in muscle effort to activate the device. By increasing the strength in the user's hand even when it is not used with energy, the device can be used by patients with a low level of muscular activity in the damaged area; additionally, considering the range of weights of similar devices, low weight was obtained with this design. On the other hand, this device does not contemplate the abduction and adduction movements of the thumb that are required for many activities of daily living, and the control system takes up a lot of space in the wrist-forearm of the user, which could be uncomfortable for some activities.

Of all people who suffer a stroke, about 80% to 90% usually have losses in the motor functions of the hands; for this reason, people with such incidents require passive therapies with physiotherapists reinforced with exoskeleton training at home; however, exoskeleton robots developed mostly have disadvantages of weight and control. For this reason, in [16], a prototype exoskeleton with optimal design was designed to be used in rehabilitation exercises of hand functions. For this purpose, an exoskeleton was designed with aluminum alloy material and 3D printed parts, linear actuators were used for each finger, and a general servo actuator was used to activate the required movements. To send the signal, a control circuit is used that, through a graphical interface, gives four options of hand position. The design was optimized to reduce weight through software topology optimization. In the end, a weight of 0.45 kg was obtained for the optimized exoskeleton and the ranges of motion were recorded. After design optimization, the quality decreased a little, but the overall feasibility went up. This proposed exoskeleton has a friendly interface so that the patient using it can perform passive exercises when outside a clinical center; the ranges of motion are good, as well as the weight reduction. However, strength tests are still needed to know how optimal it would be to perform ADL, and it has a very subtle design that needs to be improved.

Considering the factors mentioned above, this project aims to create a cost-effective hand exoskeleton prototype designed to enhance daily activities, offering advantages over existing models. The primary goals are to ensure it is lightweight, easy to adjust, and capable of providing ample strength to facilitate common tasks that may have become challenging due to hand injuries or impairments. Hybrid robotics will be used for the development of this exoskeleton since the prototype will have soft elements for the transmission of movement, and rigid elements as support for more precise movements. As for movement intention detection, in order to reduce costs, EEG and EMG sensors will be dispensed with and resistive force sensors on the fingers will be used as a replacement. Tests on the device will include measurement of grip force and lifting of everyday objects.

First, we will delve into the methodology, which comprises several key steps. We will begin by evaluating the requirements, a crucial phase in outlining our approach. Subsequently, we will discuss the meticulous process of material selection, which plays a pivotal role in exoskeleton development. Following this, we will provide an in-depth exploration of the exoskeleton's design and construction, elucidating the intricacies of its development.Moving forward, we will delve into the empirical aspect of our research, where we will present the results obtained from rigorous strength tests. These tests will not only highlight the exoskeleton's capabilities but also its effectiveness in handling various objects, shedding light on its practical utility.Lastly, we will embark on the conclusion and discussion phase, offering valuable insights gleaned from our research. Within this section, we will draw comparisons with existing devices in the field, providing a comprehensive view of our contributions and potential advancements in exoskeleton technology.

2. Materials and Methods

The present work seeks to develop an exoskeleton that can be low-cost and efficient for the rehabilitation of people with dexterity problems in the hand. To carry out this work, first of all, an evaluation of the requirements for the exoskeleton is made, and then a selection of materials is made. We proceed with the design, and finally, the tests are carried out.

2.1. Evaluation of Requirements

The exoskeleton must be suitable for use in ADL by those who have suffered some kind of accident or injury that caused a malfunction in the hand, so the exoskeleton should be able to increase the force exerted by the patient's hand and resemble the force exerted by a healthy hand (50 N or more) [17]; also, it should achieve the ranges of motion produced by the hand, at least enough to allow these people to develop most daily activities.

In the development of these devices should be taken into account, apart from functionality, they must have a good degree of comfort for the user because if you want, the patient can perform rehabilitation exercises in their own home in addition to a clinical center, and taking into account that will have the device on as long as possible for the development of ADL, the exoskeleton in question must be light, easy to put on and fit the hand of each person without affecting comfort, in addition, to help people who use it to regain their independence, the exoskeleton must allow the user to put it on without the help of someone else [18]. Another aspect to consider is the activation of these devices by the intention of the wearer; for this, many approaches contemplate in their design the use of EEG or EMG sensors [19]; however, the inclusion of these sensors increases the cost of the exoskeleton, causing that not all people can acquire it. To address this obstacle, some other, cheaper sensors with sufficient efficiency should be used so that the exoskeleton can perform as expected.In this sense, the functioning of the exoskeleton to be developed in the present work would be as shown in Figure 1.

2.2. Components Selection

First of all, it is required to know the user's movement intention, and from this, the actuators can be activated; in [15], resistive force sensors are used, and based on this, in the prototype that will be developed in this work it is planned to use the FSR 402 sensor, which changes the value of its resistance according to the force applied in a certain area (force range: ~0. 2 N - 20 N) [20], due to the size of that area and its circular shape (diameter: 13 mm) these will be located below the fingertips, so when the user tries to flex the fingers will exert pressure on the sensors, whose resistive value changes will be read by the controller and activate the servomotors, and when pressure is stopped the exoskeleton should perform the extension movement. To exert the movement, there will be MG995 servomotors that will be attached to wires with an outer coating in order to have an operation similar to that of a Bowden cable [21]; these wires will run along the outside of the hand, according to the rotation of the servomotor axis, the flexion and extension of the fingers will be performed. The force delivered by this servomotor (Table 1) is sufficient to mimic the movement and force exerted by a real hand [22]. For the controller, many on the market could perform the required operations; therefore, aiming at the objectives of lower costs and lighter weight, the Arduino Nano board containing the Atmega328 controller will be used. This controller will receive the variations in the force sensor and activate the servomotors.

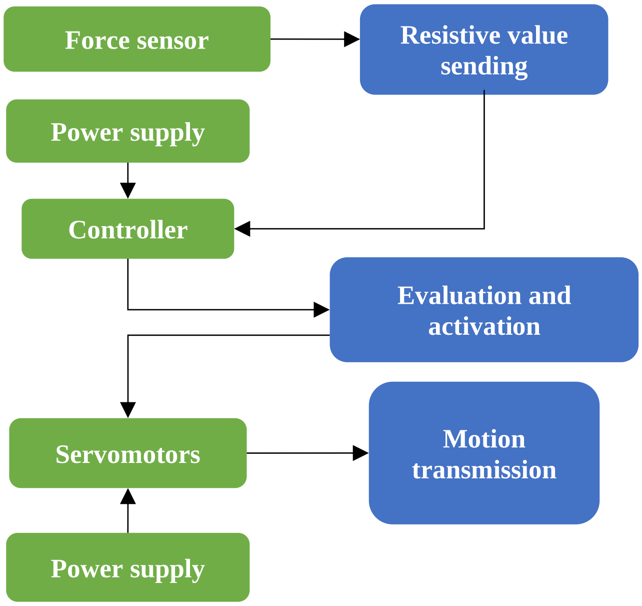

Fig. 1 Block diagram of the proposed exoskeleton

Table 1. Technical specifications of the controller and servomotor

Component	**Model**	**Operating Voltage**	**Torque**
Controller	Arduino Nano	5V	-
Servomotor	MG995	4.8 – 7.2 V	~98 N·cm (at 6 V)

2.3. Elaboration of the Exoskeleton

The prototype will occupy from the fingertips to the forearm, part of the devices will be located in the front part of the arm (Figure 2. a), such as the force sensor, the Arduino Nano board, and a servomotor for the thumb movement; in the back part (Figure 2. b), two servomotors will be located, one of them will transmit the movement to the index and middle fingers, and the other, to the ring and little finger.

3. Results

For the circuit (Figure 5), the three servomotors are considered with a parallel configuration for the power supply. At the same time, the pins for control by pulse width modulation (PWM) are connected to three digital outputs of the Arduino Nano board. To obtain the variation in the force sensor, it works in conjunction with another fixed resistor in such a way that a voltage divider is obtained. This variation is read by means of an analog pin of the controller; to place the sensor, a quadrangular structure attached to the index of the quantum was elaborated in whose inner face of the lower side the sensor is placed so that contact can be made with the tip of the index when it is flexed. For the power supply of the whole device, two separate power sources are considered; one feeds the controller, while the other is for the servomotors. The reason for this is that the servomotors consume currents greater than those that can deliver the Arduino Nano board.

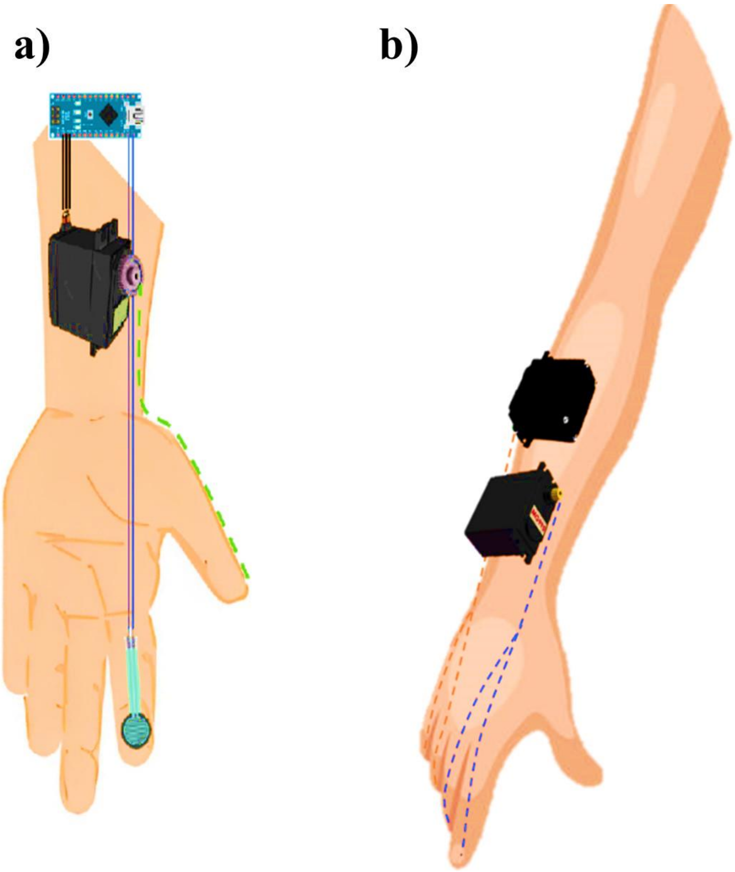

Fig. 2 Conceptual diagram of the device: a) anterior view of the arm; b) posterior view

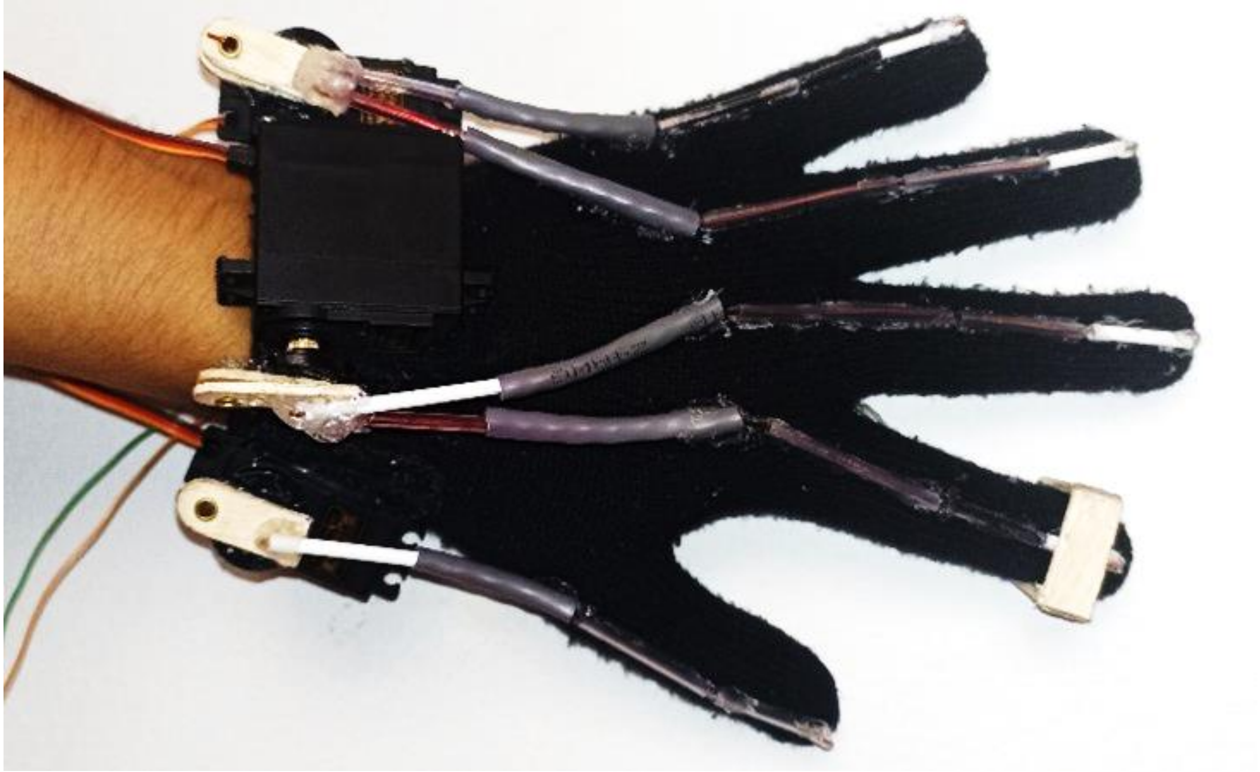

Fig. 3 Prototype of the exoskeletal glove showing the movement part

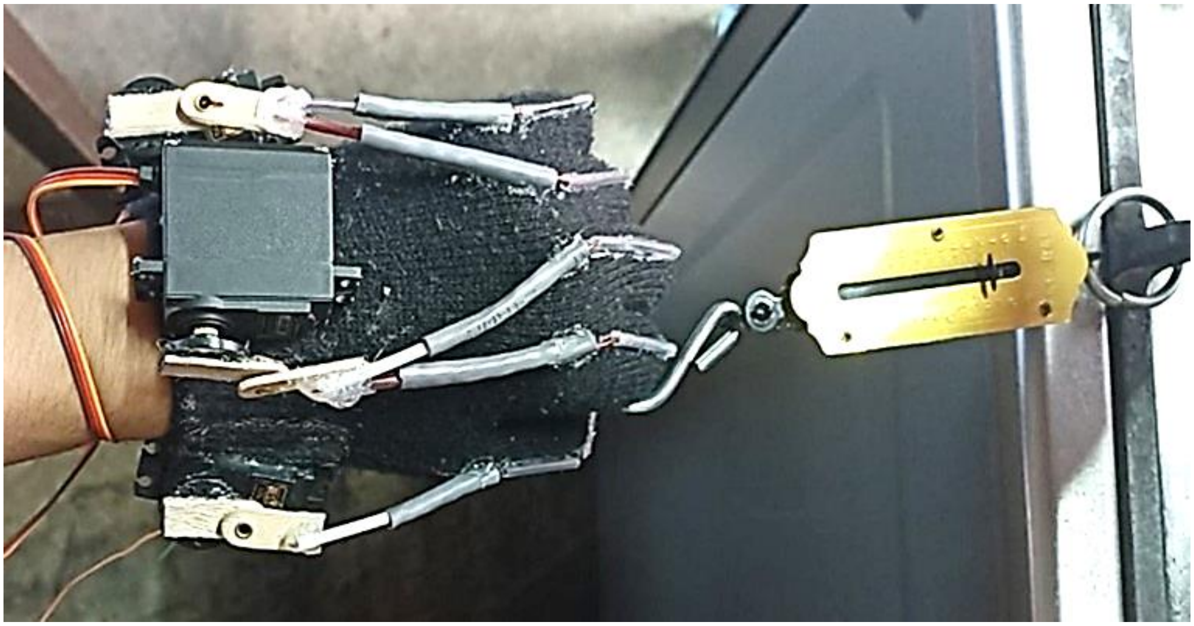

Fig. 4 Performance of force tests with a dynamometer

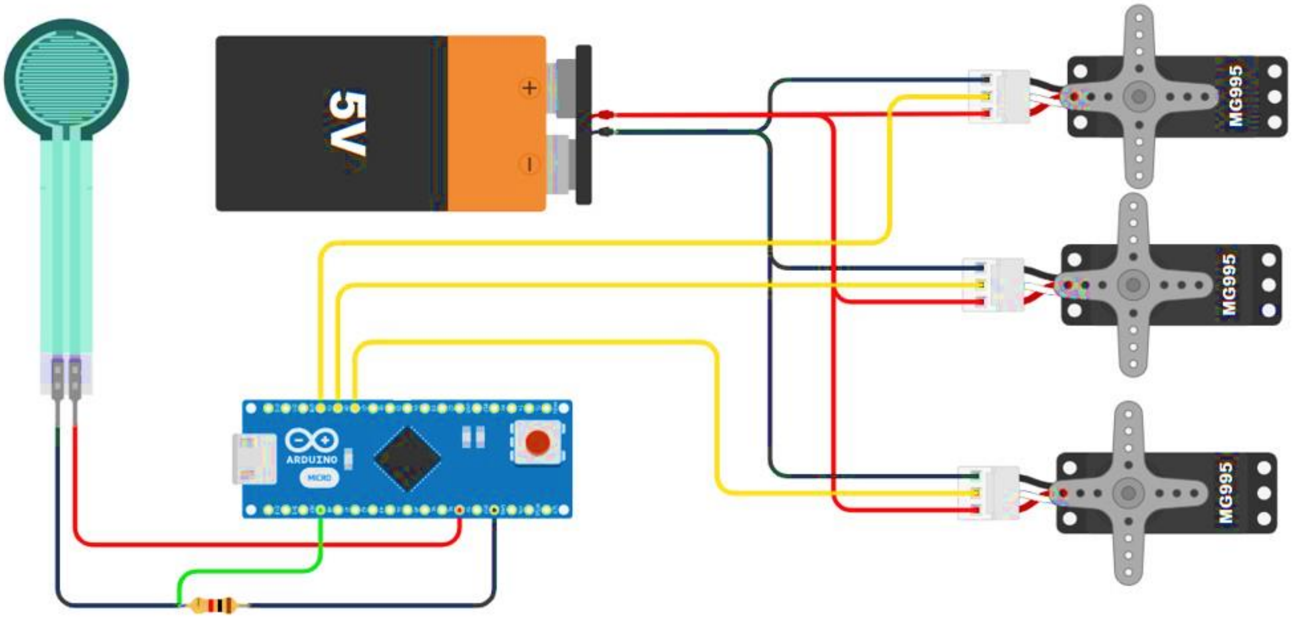

Fig. 5 Electronic circuit of the device

Table 2. Results of the force exerted according to some angles of rotation of the servomotor

Servomotor degrees of rotation	Force exerted
120°	19.61 N
150°	24.52 N
180°	29.42 N

Fig. 6 Objects used for the grip tests, in the shape of sphere, cube, cylinder and flat rectangular (from left to right)

Table 3. Comparison of the exoskeleton developed in this work with other exoskeletons

Device	Type of robotics	Force transmisión mode	Number of actuators	Maximum force (N)	Weight (g)	Type of control
This study	Hybrid	Wires based on Bowden cables	3	29.42	200	Force sensor
Randazzo et al. [21]	Soft	Artificial tendons based on Bowden cables	Not mentioned	20	50	EEG
Rose y O'Malley [3]	Hybrid	Bowden cables	7	83	220	EMG
Nazari et. al. [15]	Hybrid	Sliding blades	5	8 (on one finger)	228	EMG
Bützer et. al. [18]	Hybrid	Sliding blades	2	6 (on one finger)	148	Buttons, switch and potentiometer
Li et al. [13]	Hybrid	Steel strips	5	18.7 (on one finger)	401	EEG

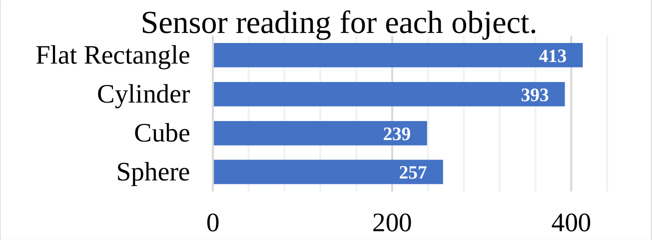

Fig. 7 Results of the grip tests for each object shape

To transmit the circular motion of the servomotors to linear motion, the crank-crank mechanism is used; the crank is connected to a cable that is attached only to the crank and to the dorsal part of the glove where the distal phalanx would be located. At the same time, an outer sheath is distributed along the entire length of the wire and is attached to the glove so that only the wire can move while the outer structure remains still and conducts the desired movement. The exoskeleton glove is shown in Figure 3.

3.1. Experimental Tests

To measure the force that the proposed exoskeleton could exert, a dynamometer was used with one of its ends attached to a fixed structure to ensure that the movement is only exerted by the exoskeleton (Figure 4); three tests were performed, each with different rotation angles for the servomotor: 90°, 120° and 180° (maximum bending).

In addition, it was tested how well the exoskeleton adapts to hold common objects with different shapes; for this purpose, the following objects were used: a bottle, a cell phone, a medium sphere and a Rubik's cube (Figure 6); also, a record of the force sensor readings were made when holding the aforementioned objects, previously, the minimum and maximum values that a finger can exert on the pressure sensor were observed taking into account that these values are within the range of 0 to 1023.

The results of the force test are summarized in Table 2. The measurement on the maximum and minimum values exerted by a finger on the sensor ranged from 52 to 666. Based on this, the values for each object are shown in Figure 7. The weight of the exoskeleton was also measured, considering only the parts to be carried by the hand, obtaining a weight of 200 grams.

4. Discussion and Conclusion

The exoskeletal glove we have designed possesses ample force to securely grasp various everyday objects, rendering it highly practical for performing Activities of Daily Living (ADL). Moreover, its lightweight construction and comfortable design make it suitable for extended periods of use, with users finding it non-intrusive. Additionally, the affordability of this device ensures accessibility to a broader range of individuals. However, it's important to note that the force exerted by this glove may not match the levels achieved by some other exoskeletons documented in the literature. For a comprehensive comparison of key characteristics, please refer to Table 3, which outlines the distinctions between our exoskeletal glove and others. The present research introduces a novel perspective in the evaluation of exoskeletons, particularly from an economic standpoint. In this context, our results share similarities with the study by [10], which emphasized the importance of grip strength on objects and highlighted the difference in force between the fingers. Additionally, [11] played a fundamental role as a source of inspiration for the development of our research, as their Velcro-fixed glove allowed both their prototype and ours to be adaptable to different hand sizes. On the other hand, it is worth mentioning that [3] diverged from our results, as their focus was on creating motor recovery exercises for spinal injuries, while our proof of concept centered on measuring force and reactions on various surfaces. Collectively, our findings provide a solid starting point and establish a foundation for future research at our institution, with the aim of promoting the dissemination and development of new wearable exoskeleton-based devices applied to the hands. This innovative approach not only has the potential to improve the quality of life for individuals with motor disabilities but can also open new opportunities in the fields of rehabilitation and assistance on a global scale, thereby contributing to a more inclusive and healthier future for all. As part of our future endeavors, we recommend enhancing or modifying the components acting as Bowden cables to enhance the transmission of motion. Optimization of the device design could involve the utilization of 3D-printed parts to improve the conversion of circular to linear movement and the relocation of the pressure sensor to a position near the index finger. Furthermore, we suggest exploring the possibility of incorporating additional parts or straps to better tailor the device to the user's wrist and finger phalanges, preventing any loss of movement due to the elasticity of the glove material.

It may also be beneficial to consider alternative glove types as a base. In conclusion, we have successfully developed an exoskeletal hand glove designed to aid in motor rehabilitation following accidents that impact hand mobility. Our approach involves a force sensor capable of detecting the user's intention to move through subtle index finger motions. This triggers the activation of servomotors, providing substantial torque. Consequently, patients can grasp various daily objects, while the device's progressive force regulation assists users in recovering their hand-gripping abilities through consistent practice.

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