SMA-Based Soft Exo-Glove

David Serrano, Dorin Copaci, Janeth Arias, Luis E. Moreno, and Dolores Blanco

***Abstract*—Nowadays, robotic technologies are used in many fields, one of them is medicine. The breakthrough of technologies has enabled the development of robotic devices for rehabilitation therapies. The exoskeletons can be found as robotic device for rehabilitation therapy, whose rigidity limits the user's freedom of movement, complicating his interaction with the environment in an easy and natural way. To overcome this current limitation, researchers invest effort in the development of soft devices, wearable, portable and comfortable for patients, maintaining the rigid exoskeletons performance. The soft exo-glove proposed in this work, accomplishes three main previous features. It is actuated by Shape Memory Alloys (SMA) that reduce the device weight and turn it into a portable exoskeleton. The exo-glove is easier to wear and it is comfortable. The proposed exo-glove represents a safe and adaptable solution for the human hand rehabilitation therapy with special emphasis on the activities of daily living (ADL). We are going to analyze exo-glove performance during ADL movements, e.g. gripping different objects with diverse dimensions, in which, other exoskeletons have some limitations. In terms to address this challenge, a specific position controller was designed which enables the single displacement of each finger with a linear actuator precision of 5%.**

***Index Terms*—Soft exo-glove, shape memory alloy, hand gestures, rehabilitation device.**

I. INTRODUCTION

ACCORDING to Eurostat [1], in 2019 20.3% of the population of the European Union was over 65 years of age. The impact of demographic aging will be very significant assuming an increase in social spending. This aging of the population causes a higher prevalence of different diseases like musculoskeletal injuries, neurological damage, strokes, neurodegenerative diseases, etc. requiring the attention of the health systems. Rehabilitation therapies are one of the main treatments required by society to healthcare system. Governments must face the growing expense of these treatments to provide well-being to the population. When hospitalization is necessary for therapies, medical expenses are increased. In one study, it has been estimated [2] that rehabilitation therapies for neurodegenerative diseases of 64 patients for one month cost approximately 27 000 € without including the administrative costs of hospital. In order to reduce healthcare expenditure, different lines of research have arisen. Among them, robotics devices have been developed to improve rehabilitation therapies and minimize health expenses. One of the most promising devices is assistive robotic technology based on exoskeletons which are placed over the lower and upper limbs to recover the motor function. In this way, patients can recover their ability to carry out activities of daily living (ADL). In Pons [3], effectiveness of robotic therapies has been proven in comparison with traditional therapies.

During ADL, the human body movement uses different degrees of freedom (DOFs), which enables the efficient and continuous performance of dynamic tasks, interacting with the environment in a robust and precise way. Due to the DOF limitation of rigid exoskeletons, these movements are restricted by the rehabilitation device during its use, restricting the user movement. The design of soft robots, based on the use of deformable materials, resulting in a biomimetic design that replicates the behavior of organic tissues. This design philosophy has turned rigid and cumbersome robotics devices, into something we could call exo-suits: motorized, lightweight and comfortable clothing-like devices. The current tendency evolves towards wearable and portable devices, which patients can carry at home. Therefore, soft devices can be used at the hospital with the therapist's guidance during an initial period of rehabilitation. Then, the patient can follow therapy at home, with remote therapist supervision.

Currently, rehabilitation therapies depend on the injury of patients. The most important diseases which require mobility rehabilitation are long-term injury, stroke, neurodegenerative illnesses and cerebral palsy. Furthermore, the type of therapy depends on the stage of rehabilitation, active and passive treatments are the main types. During active therapies, robotic devices can detect the user's intention of movement and help to complete the movement that patient wants to do; trying to involve patients in rehabilitation. On the other hand, passive therapies carry out repetitive movements. Robotic devices assist in the analysis of patient improvements because sensors (placed in exoskeletons) provide accurate and objective measurements of the movements achieved by the patient during the last therapy session. Thus, physiotherapists are able to diagnose any injury and evaluate the enhancement of the rehabilitation through robotic devices.

This letter contains six sections. Section II analyze previous works related by hand exoskeletonts. Section III presents the soft exo-glove design with the used actuators. The Section IV,

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presents the test bench for hand exoskeleton where tests have been done. Experimental results are covered in Section V. Section VI show a discussion of main results of this work. Section VII fulfills the conclusions of this work.

II. LITERATURE REVIEW

There are soft exoskeletons for rehabilitating different joints of the patients, including actuated suits [4]. However, hand exoskeletons are the most difficult to implement, due to the human hand complexity and dexterity. The human hand has many DOFs and during ADLs, hand movements are very complex. Many applications implement hand exoskeletons for any stage of rehabilitation therapy [5]. Furthermore, some of them provide hand assistance in ADL [6] too. Glove devices stand out from the current rehabilitation soft-hand-exoskeletons solutions [7], [8], [9], [10]. These devices integrate different actuators such as motors with Bowden cable transmission or pneumatic muscles [11].

In Chen et al. [12], the soft glove is actuated by five DC micromotors and the movements are transmitted by artificial tendons that are made out of nylon and embedded in the glove. Regarding sensors, the device uses ten flexible and bendable sensors to capture the hand's motion for gesture recognition. This device only implements flexion movement of the fingers and does not enable the thumb opposition. The functionality of Rudd et al. [13] is similar, however in this case extension movement is actuated by a spring that enforces the recovery of finger initial position after the flexion movement. Specially, stroke patients usually need recover extension movements because, after cerebrovascular accident, their hand is closed due to post-stroke spasticity [14]. Furthermore, there are rehabilitation devices which focus on recovering the mobility of three fingers (thumb, index and middle) [15].

Pneumatic actuators are used in Cheng et al. [16]. In this work the thumb is fixed by a splint and the rest of the fingers are activated to achieve flexion and extension movements. This way, the device carries out grasping, 2-finger pinching or tripod pinching movements. Another work that actuates all fingers is explained in Jiang et al. [17]. This device is actuated by pneumatic actuators too.

Several research of soft robotics use artificial muscular fibers with the aim of replicating the human muscles performance, among them the Shape Memory Alloys (SMA) are used as an artificial muscular fiber. This bio-inspired actuator is employed in order to move each finger [18] independently or to move the whole hand [19]. In this case, exoskeleton was used to assisting astronauts during outer space tasks. This exo only actives flexion actuators, and, to control the device, hall effect sensors are used. Therefore, compared to the work shown here, the design of the sensorized box is changed, also introducing the duplication of the displacement to reduce the length of the actuators. The design of the glove has also been modified to facilitate its placement and make it more comfortable for the patient.

Another main feature of exoskeleton design is its customization because there are different patients with different illnesses and different hand sizes. Regarding the customization of the glove, researchers design gloves that are adjustable [20] with elastic materials, silicones, etc. In other cases, a glove for each patient can be developed with 3D printers [21]. The development has to achieve the glove's comfort and functionality in order to avoid patients' damaging and to reach effective therapies.

One part of the work was how to determine the main gestures for ADLs. There are a great variety of hand positions depending on the task that is going to be carried out. In Saudabayev et al. [22] a general classification of ADL gestures is established. Many of them require a lot of dexterity; however, our exoskeleton is oriented to achieve a high level of rehabilitation in daily living but, also, simplifying movements. For example, the most important movement of the hand during ADLs is the pinch movement. This movement is achieved specially through thumb opposition and index flexion. Therefore, it is important that device is able to rehabilitate each finger independently, and afterwards, their movements are combined to reach specific hand positions to carry out specific tasks (grasp objects or hold objects, pinch, etc).

In this work we propose a soft exo-glove device for rehabilitation, actuated with a SMA-based actuator, with many DOFs. It offers the possibility of individually extending and flexing each finger according to the movement intended to rehabilitate and, other times, according to the user's intention of movement. All this system represents a compact, low-weight, easy-to-use, low-fabrication-cost solution with a noiseless operation.

III. SOFT EXO-GLOVE DESIGN

Recently, our research group have focused on the development of exoskeletons devices actuated by SMA; due to its characteristics such as: low weight, noiseless operation and low cost. These devices are particularly focused on upper limb rehabilitation after different disorders such as stroke, cerebral palsy, muscular dystrophy, or traumatic brain injury. The hand is a highly complex and multi-faced mobile effector organ which through a complex system of muscles, ligaments, tendons, bones, and soft tissues, gives the possibility to carry out tasks such as grasping and manipulating objects. Hand function plays a fundamental role in performing ADLs, maintaining an independent and healthy quality of life. When one of those hand affections occurs, the quality of life decreases and the affected person even becomes codependent on another person. The proposed device in this work is a soft exo-glove actuated by means of tendons moved by SMA-based actuators. To perform complex movements with the soft exo-glove, the tendons routing is a key task. If the route of tendons for the flexion-extension movement of the phalanges is relatively simple, the human hand present in the ADL different phalanges movements combination including abduction and adduction e.g. the gripper. Different methods of tendon routing within the glove have been studied by our research group before, being the final version, the one presented in this work. During these studies various tests were driven such as: a little metal piece was placed on the fingers top, to avoid bending the tip of the glove or passing the thread over the finger for the extension movement. In other tests, it was observed that the finger did not achieve the adequate movement, because, in first tests, tendons are fixed


(a)

(b)

Fig. 1. (a) Attachment points between the tendons and the glove: left side for the flexion movement, right side for the extension movement. (b) Tendon routing over the soft exo-glove: for the flexion movement - right side and for the extension movement - left side.

in fingertip, and this tendon routing generated an uncomfortable movement, especially during extension movement, so its tendon routing was modified. Also, during tests, it has been evaluate thumb opposition movement to complete the whole movement correctly. The final tendon routing scheme can be seen in Fig. 1. This tendon routing was obtained by the trial and error method, actuating the tendons and observing the glove movements. The main parameters which have been considered in tendon routing tests, is glove comfortability and bioinspired movements of exo-glove. Achieving a correct tension of the artificial tendons through routing is one the problem with final tendon routing.

The routing points shown in Fig. 1, are the key to obtain the necessary finger movements and, thus, hand gestures for rehabilitation or ADL activities. The combination of different tendon contraction, due to the activation of actuators, can result in different movements, usually on the ADL, such as grasping, gripping, pulling the finger into a fist and so on. The number of tendons needed by the hand to achieve these movements is six for the hand flexion and five, for the hand extension. For the flexion movement the routing of the tendons is more complex. Apart from flexion movement, the thumb finger needs a special routing for two actuated DOF. One tendon goes from the thumb to the little finger (red wire in Fig. 1), in order to thumb flexion and another tendon passes between the little and ring finger (green wire in Fig. 1), to achieve thumb opposition. This routing gives us the possibility to gesture as a gripper.

In Fig. 1, the main points of tendon fixation and the tendons over the proposed soft exo-glove are represented. For the extension, the most critical tendon routing point is in the distal phalanges where the glove tip-bending can occur if the glove is not perfectly adjusted to the user hand. This type of configuration, where the tendons are making a loop over the fingers, avoids the glove tip-bending.

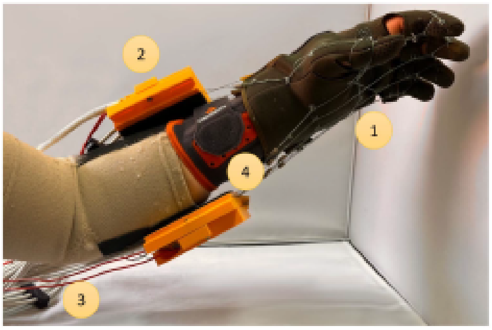


Fig. 2. Hand soft exoskeleton. 1. Glove. 2. Sensorized Box. 3. SMA actuators. 4. Wrist support.

In the human hand, when the fingers are flexed, in the distal phalanges movement, it can be observed that the trajectories are not parallel. These trajectories are slightly deviated to join at a common point over carpal bones that compose the wrist. This articulation is immobilized with a wrist support (Fig. 2) to avoid a non desired displacement in this joint. In the soft exo-glove, for a better adjustment with the fingers movement, this characteristic was implemented. This can be observed in the tendon routing fixed points on the flexion side of the soft exo-glove (the nearest points of the forearm).

The most important movement of the thumb is opposition, in which abduction coupled with rotation at the carpometacarpal (CMC) joint moves the thumb toward the tip of the little finger [23]. This movement can be achieved due to two tendons which actuate the thumb in the flexion side of the soft exo-glove; one making a loop over the little finger and another one firstly routed along to the palm and afterwards deviated to the forearm.

Furthermore, to scale this device to different users, with different heights, weights and impairments, the proposed device needs to be adaptable. This way, it is easy to develop multiple gloves with different sizes in order to provide comfort. This feature enables us to reach the maximum position of each finger without losing the range of angle. The glove should be tight-fitting too. For that reason the glove material is neoprene which is elastic enough to fit the hand of the patient. On the other hand, due to the tendons material (textile), the glove material (neoprene) and due to its easily detaching from the electronics and actuators, the device can be easy cleaned and washed. As it can be observed in Fig. 1, in the palm of the hand, the finger area is open to wear and remove exo-glove easily. These operations are solved in less than one minute.

A. Actuator Design and Control

As we have mentioned previously, for the soft exo-glove actuation a SMA-based actuator is used. The actuator consists of fibers of a nickel-titanium alloy which present a special behavior, the shape memory effect (SME) and superelasticity. Due to its properties, this material can stretch to an extreme length, between to transformation phases austenite (at high temperature) and martensite (at low temperature) without incurring in plastic

Fig. 3. SMA-based actuator-left side (1-Bowden Cable, 2-PTFE Tube, 3-SMA Wire, 4-Terminal Unit); Actuator schematic concept -right side.

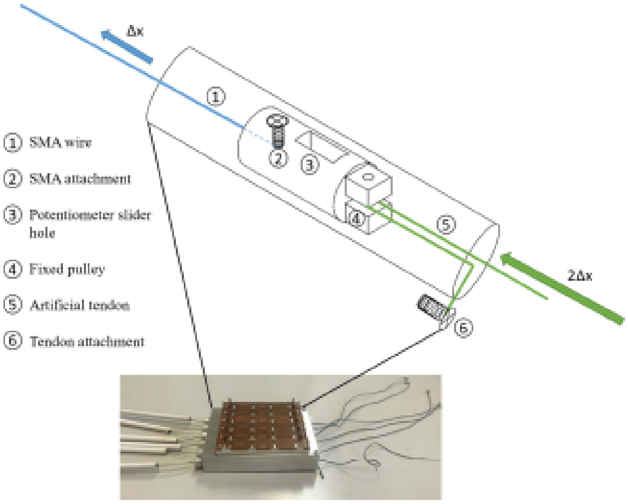


Fig. 4. Sensorized box and representation the cylindrical piece which moves within a guided rail.

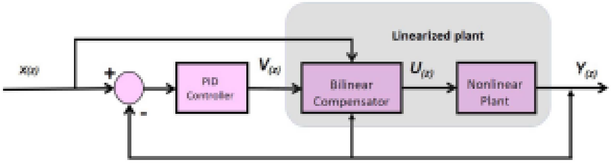


Fig. 5. BPID control algorithm.

deformation. In this work, the Joule effect is used to generate heat to the fibers where the electric energy is turned into thermal energy and this energy into mechanical work. According to this transformation, between the martensite phase and austenite phase, the SMA fibers contract until 4% of their length [24].

The SMA-based actuator structure developed by our research group consists of a SMA wire (0.38 mm diameter, 90 °C activation temperature, from Dynalloy [25]), a polytetrafluoroethylene (PTFE) tube and Bowden cable. The SMA wire is inserted into a PTFE tube that isolates it electrically and thermally. Then, the wire with the PTFE tube is placed into a Bowden cable which provides flexibility to the actuator. One side of the wire is fixed with a terminal unit while the other one is left unattached [26]. Therefore, the Bowden cable is able to transmit the movement of the SMA wire. Thus, the displacement needed it is generated. The SMA-based actuator and the schematic assembly concept are shown in Fig. 3.

In order to calculate the actuator length, the maximum displacement of the exo-glove tendons is needed. It was experimentally found that the displacement of tendons is approximately 80 mm according to the proposed routing for a male adult. Keeping in mind that the displacement of tendons depends on the size of the glove and hand dimensions of the patient. Addressing that the SMA-based actuator generates a displacement of 4% of its total length, the actuator need to be at least 2 m long to generate a displacement of 80 mm for a male adult. This length is excessive, for this reason, a displacement multiplier based on a mechanical solution with a pulley in each actuator has been developed (Fig. 4). It duplicates the movement and makes the wire length 1 m. Due to the actuator flexibility property, it can take the shape of the human body shape, adapting to the upper limb.

The actuator is connected to the exo-glove tendons in a sensorized box shown in Fig. 4. A cylindrical piece moves within a guided rail, where the tendon and the SMA wire are connected. The cylindrical piece is displaced by the SMA contraction which drags the glove tendon. The cylindrical piece is directly connected to a linear potentiometer PTA4543-2015CPB103, used for the displacement measurement.

The electronic hardware consists of the position sensors (potentiometers), a microcontroller and a power circuit required to control the SMA-based actuators. The electronic power circuit for SMA wires is based on MOSFET transistors. The transistors are activated by Pulse Width Modulation (PWM) provided by the controller. The transistors open and close the circuit with a power supply to the actuators. With these electronics, the control hardware architecture can manage six different actuators (each actuator with one or more SMA wires).

The controller board is based on the STM32F407 Discovery kit [27], from STMicroelectronics, which is programmed with Matlab/Simulink [28]. This manages signals from the sensors, executes the control algorithm for controlling the actuators, and generates the required PWM signals.

The SMA-based actuator presents nonlinearities and a considerable hysteresis which constrains the use of nonlinear controller's methods for better performances. A Bilinear Proportional Integral Derivative (BPID) controller is used to compensate this non-linearities, which schematically is presented in Fig. 5. This is based on previous works and the literature [29], [30], [31].

In Fig. 5 the BPID controller is schematically represented where: X represent the desired reference, V is the control signal generated by the Proportional Integral Derivative (PID) controller, U represents the control signal rectified by the bilinear term and Y represents the actuator position response. The performance of this control algorithm was previously tested and compared with other two controllers, a conventional PID and a commuted feedforward PIPD which switches between a Proportional-Derivative (PD) controller and a feedfordward plus Proportional-Integral (ff+PI) controller [30].

The formula of bilinear compensator that is implemented in BPID controller is (K_b is bilinear gain):

$$\frac{U(z)}{V(z)} = \frac{1 + K_b X(z)}{1 + K_b z^{-1} Y(z)}, \tag{1}$$

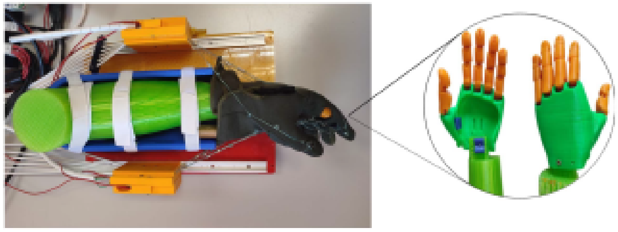


Fig. 6. Test bench for hand exoskeleton.

Therefore, PWM signal controls the current supply of SMA actuators, according to the following equation of PID controller:

$$I(z) = \left[K_p + \frac{K_i}{1 - z^{-1}} + K_d\left(1 - z^{-1}\right)\right] E(z), \qquad (2)$$

where $I(z)$ is the PWM duty cycle, K_p is the proportional gain, K_d is the derivative gain and K_i is the integral gain. $E(z)$ is the error between the reference and the output.

IV. TEST BENCH FOR HAND EXOSKELETON

Current design has been implemented to enable the execution of tests over the hand exoskeleton; moreover, the device is thought that patients can used during their rehabilitation therapies.

In case of the test bench (Fig. 6), to check the functionality of the hand exoskeleton, an artificial arm with an artificial hand to simulate human upper limb has been built. Dimensions have been calculated for a human-being with a 175 cm height. The arm is a fixed structure without movements. The size of the forearm has been calculated according to the human height [32]. The length of forearm is 14.6% of its height, so it is 25.5 cm. The length of the hand is 10.8% of its height; therefore it is 18.9 cm. The hand has been designed with flexible parts to mimic human movements. All knuckles have been made with flexible plastic in a 3D printer. Fingers achieve a complete range of movement, like a human hand including opposition of the thumb. This movement is important for ADL.

Regarding the wrist, the articulation has been developed without movement in order to avoid losing displacement of the wire. Hence, the movement of the SMA is fully transmitted to the fingers.

Concerning comfort, the test bench has adjustable parts to work with all types of patients' forearms and hands. The arm is fixed by Velcro tape. Also, the actuators boxes have been placed in an appropriate position so that the glove tendons have the accurate tension to carry out the whole movement without losing displacement. The boxes can slide on a track to tense the artificial tendons.

V. RESULTS

In order to evaluate the design of exo-glove and the algorithm to control the device. Some gestures, which are useful in ADLs, have been chosen.

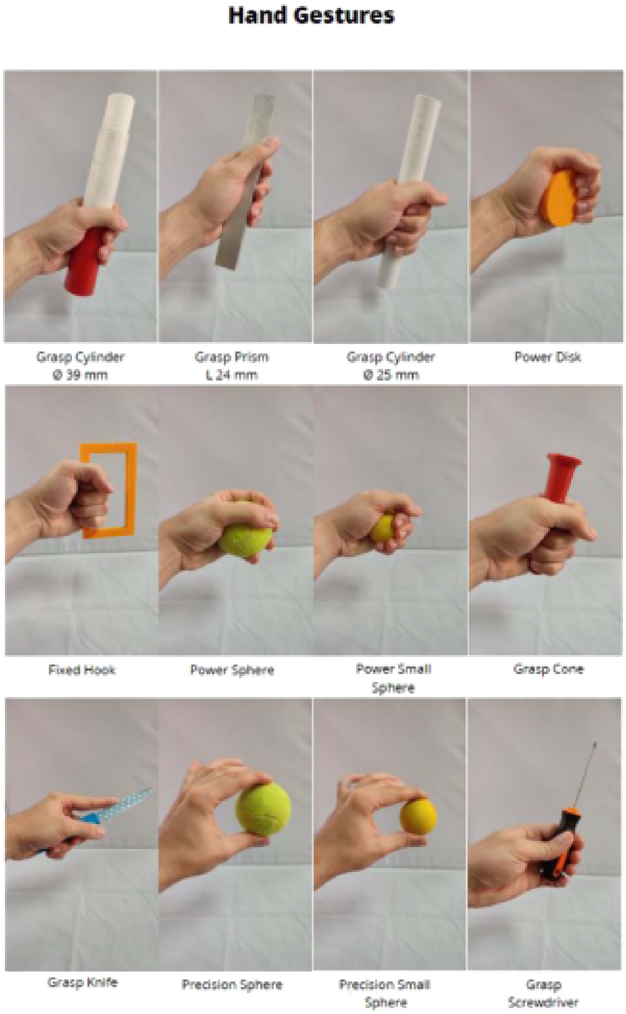


Fig. 7. Hand gestures.

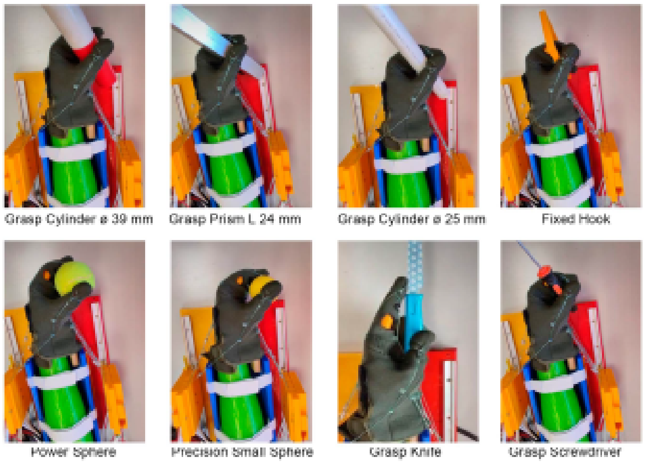
A. Hand Gestures

As it was mentioned in the introduction, the soft exo-glove is used to carry out rehabilitation therapies to recover hand mobility and dexterity, achieving ADLs movements.

Hand gestures which are shown in Fig. 7, are simple to develop rehabilitation therapies. This way, patients recover the mobility and they can carry out ADLs.

ADLs require high levels of dexterity, specially, thumb opposition which enables the achievement of certain movements like grasping objects, (for instance, knifes, screwdrivers, etc.). The movement called Fixed Hook in Fig. 7, is important because it allows reaching the task of opening a door with a handle. Furthermore, in Fig. 7, it is shown that grasping a knife is an important movement given that it is one of the main movements of the hand during eating tasks.

All hand gestures have been tested in the test bench. The system receives reference signals for each finger with the aim of developing the movements. The reference signal consists in a step for each actuator. This signal represents the displacement of the actuator which is required to carry out the complete movement of each finger.


Grasp Cylinder ⌀ 39 mm Grasp Prism L 24 mm Grasp Cylinder ⌀ 25 mm Fixed Hook

Power Sphere Precision Small Sphere Grasp Knife Grasp Screwdriver

Fig. 8. Exoskeleton tasks during tests.

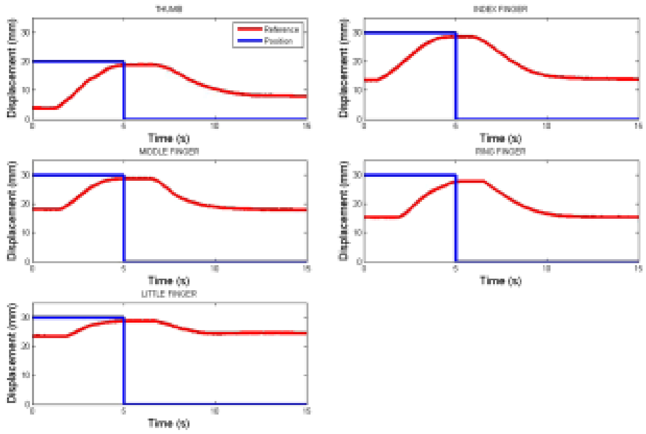


Fig. 9. Actuator position of each finger during extension movement in "Grasp Cylinder D25 mm".

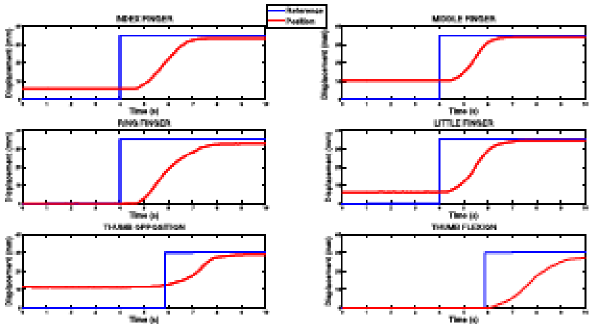


Fig. 10. Actuator position of each finger during flexion movement in "Grasp Cylinder D25 mm".

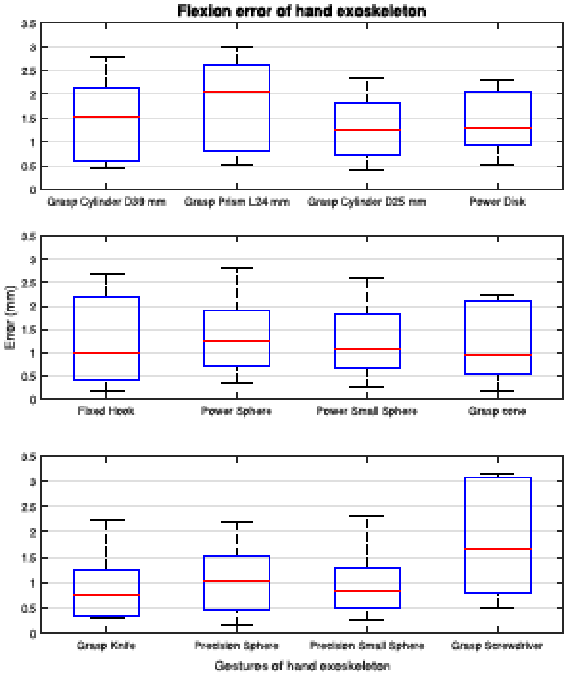


Fig. 11. Error of exo-glove during flexion hand gestures.

B. Evaluation Hand Gestures Reached

All of the hand gestures that have been shown before, and other simple ones like fist, hand-opening and pinch, have been tested in the test bench to evaluate the range of movement of the exo-glove. In Fig. 8, some tasks of the exoskeleton in the test bench are shown.

It has been carried out 3 tests for each hand gesture of ADL. Tests consist of the system receives reference signals for each finger. Firstly, the device carries out the movements without objects to verify that the glove achieves the required displacement. A reference signal is chosen for each finger in order to grasp each object with precision without squeezing. Then, the gesture is tested with objects. In these last tests, the movement of the device starts with opening the hand, so, extension actuators are activated and their performance is shown in Fig. 9.

As it can be seen, the actuators move slowly to achieve the extension references without error. And then, the human places objects over hand palm. In this moment, the gesture is initiated. Afterwards, the exo-glove grasps the objects during five seconds and, finally, the hand is opened to drop the objects. In Fig. 10 the displacement of each finger actuator during movement can be observed. They are represented in Fig. 7 like "Grasp Cylinder ⊘ 25 mm".

It is shown that the system reaches the final position in 4 seconds approximately. Furthermore, it is observed that the thumb movements start with a delay because, first the rest of fingers carry out the movement, and finally the thumb performs its movements to hold objects and avoid crashing with the index finger. This way, all fingers can achieve the whole movement.

The parameter that has been chosen to verify the range of motion of each gesture, is the error, which is measured as the difference between the value of the reference signal in millimeters and the value of the displacement of each SMA actuator which is provided by a linear potentiometer of the sensorized box, in millimeters, too. Therefore, the error is in millimeters.

In Fig. 11, box graphics are shown which represent the error distribution of each gesture. The error distribution is composed by errors of each finger in steady state when the device does the flexion movements of the hand. In this case, only the error in flexion gesture is evaluated because it is the most important motion during hand gestures. The extension task is only carried out to drop the objects and the error in this movement is similar to flexion.

As it can be observed in Fig. 11, the maximum median of displacement error is approximately around 2 mm and the minimum value of median error is under 1 mm. Then, there are values from the error distribution which achieve a maximum of 3 mm, and minimum values near to 0 mm.

VI. DISCUSSION

Main contribution of this work is the development of an exo-glove which actuate thumb opposition, that is important movement to able grasps and grips objects. In the other hand, patients need recover mobility to carry out activities of daily living. For that reason, it has chosen gestures in order to grasp diary objects like knife or screwdriver. Grasping knife need more dexterity because it requires the movements of middle finger and thumb to support the knife and index finger to apply the force in the blade of the knife.

Another contribution of this development is that the glove can actuate flexion movements and extension movements of fingers too. These movements are important to reach complete grasps and grips like spheres.

Lastly, the development has some disadvantages or troubles which are going to eliminate or improve through future works.

Firstly, it is proposed placing sensors over the glove to measure real position of the hand and, at least, estimating the real position of the hand. After that, the exo-glove is going to validate over real patient. In these therapies, it is going to include repetitive movement of the fist, opened hand and pinch, in order to carry out a whole rehabilitation therapy.

VII. CONCLUSION

An exo-glove for rehabilitation therapy has been developed. The device is able to perform complex gestures to improve the range of movements during ADLs. Patients achieve a high level of mobility in order to be more independent during ordinary tasks.

The main advantages of the hand exoskeleton are that it can carry out flexion and extension movements of each finger independently or simultaneously to perform hand gestures. Also, one of the important contribution of this exo-glove is the opposition of the thumb. This movement is extremely important to perform the pinch gesture which allows a huge variety of grips and improves the dexterity of the hand. Gestures are reached precisely because the maximum error is around 2 mm.

Regarding the main features of the exoskeleton, its operation is considered to be noiseless because it does not use motors, and it is light-weight. Moreover, the device is portable and it makes rehabilitation therapies easier. The weight of the soft exo-glove with actuators is 2.7 Kg. Moreover, the electronic weigh is 0.8 Kg. It is an acceptable weight bearing in mind that this exo-glove can achieve flexion and extension movement of every finger when compared with others works [20] that only actuate three fingers.

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