Received January 2, 2019, accepted February 20, 2019, date of publication March 4, 2019, date of current version March 25, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2902939

SMA Based Elbow Exoskeleton for Rehabilitation Therapy and Patient Evaluation

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This work was supported in part by the Exoesqueleto para Diagnostico y Asistencia en Tareas de Manipulación through the Spanish Research Project under Grant DPI2016-75346-R, and in part by the RoboCity2030-DIH-CM Madrid Robotics Digital Innovation Hub (''Robótica aplicada a la mejora de la calidad de vida de los ciudadanos. fase IV''), funded by the ''Programas de Actividades I+D en la Comunidad de Madrid,'' and co-funded by the Structural Funds of the EU, under Grant S2018/NMT-4331.

ABSTRACT A large number of musculoskeletal and neurological disorders can affect the upper limb limiting the subject's ability to perform activities of daily living. In recent years, rehabilitation therapies based on robotics have been proposed as complement to the work of therapists. This paper introduces a prototype of exoskeleton for the evaluation and rehabilitation therapy of the elbow joint in flexion extension and pronation-supination. The main novelty is the use of bioinspired actuators based on shape memory alloys (for the first time) in an upper limb rehabilitation exoskeleton. Because of this, the device presents a light weight, less than 1 kg, and noiseless operation, both characteristics are very beneficial for rehabilitation therapies. In addition, the prototype has been designed with low-cost electronics and materials, and the result is a wearable, comfortable, and cheap rehabilitation exoskeleton for the elbow joint. The exoskeleton can generate the joint torque (active mode) or it can be used as a passive tool. (The patient performs therapy by itself, carrying the device while it collects relevant movement data for evaluation.) The simulations and experimental tests validate the solution in the first phases of rehabilitation therapies when slow and repetitive movements are required.

INDEX TERMS Antagonist control, elbow rehabilitation, exoskeleton, shape memory alloy (SMA), wearable robotics.

I. INTRODUCTION

The upper limb plays an important role in the activities of daily living (ADL) [1]. But a large number of musculoskeletal and neurological disorders can affect the upper limb reducing the subject's quality of life. This type of disorders can occur after accidents such as Stroke or Cerebrovascular Accident (CVA), Spinal Cord Injury (SCI), or different type of disorders of the motor neurons.

When this type of accidents happen, the patient can recuperate from these disorders (at least partially) with the aid of rehabilitation treatments and therapy. The process of recuperation differs in function of the type of lesion and the period of time that has passed since the accident occurred [2]. The rehabilitation therapy involves a series of repetitive movements executed by the patient with the aid of the therapist. This requires special attention; every patient needs one or more therapists, which consumes considerable health care and financial resources. Among the most promising technologies, it is considered that robotic therapies with exoskeletons are very beneficial for patient rehabilitation requiring a repetitive treatment for reeducation of lost movements. Robotic rehabilitation devices come to aid the therapists, offering a more effective and stable rehabilitation process compared to the traditional rehabilitation sessions effectuated by therapists and reducing the cost of hospitalization.

In the last decade, different devices have been developed for elbow joint evaluation and rehabilitation therapy. A broad review can be found in [3]–[5]. Most of them rely on stationary systems (Armeo Power from Hocoma [6], MEDARM [7]) or portable devices (NEUROExos [8]). In terms of mechanics, the most common tools are the end-effector devices, which are connected to the limb only at its most distal part (MIT Manus [9], ACRE [10]), and the exoskeleton-based devices, where the skeletal structure of the limb coincides with the mechanical structure of the

The associate editor coordinating the review of this manuscript and approving it for publication was Bora Onat.

rehabilitation device [8]. The actuation system of this type of devices is mostly based on electrical motors [6], [11], but devices actuated by hydraulic actuators [8], Series Elastic Actuator (SEA) [12], [13] on the elbow and wrist joint or pneumatic actuators can also be found [14]. In the pneumatic ones, one relevant example is the Pneumatic Artificial Muscle (PMA) [15]. In addition, the Functional Electrical Stimulation (FES) is also used, but it is difficult to achieve precise and repeatable movement with this technique, and it may be painful for the patient [3]. The majority of these devices present considerable weight, which in the case of portable devices must be supported by the patient. For example NeuroExos, used for the elbow flexion – extension rehabilitation, the upper arm and forearm links (including all the actuation and mechanics components) have a weight of 1.65 kg for the arm and 0,65 kg for the forearm. Another example is the orthosis proposed by Pylatiuk *et al.* [16] the exoskeleton with the actuators and electronics have a weight of 0.7 kg, but maximum 3 Nm torque in the elbow joint which is too low to mobilized the elbow articulation in the rehabilitation therapy. Other device which use DC motors such Armeo Power from Hocoma which is stationary system has a weight of 205 kg. A large part of this weight is due to the actuator weight. The Harmony exoskeleton with seven DOF (five active DOF in the shoulder, one DOF in the elbow and another one in the wrist), is a static device actuated with DC motors, harmonic drive and SEA with a total weight of 31.2 kg excluding the frame. The continuous torque of this device is 3.4 Nm on the shoulder, 13 Nm on the elbow and 1.25 Nm for the wrist [13]. DC motors and cable driven transmissions was used in the four DOF exoskeleton, MAHI Exo II [17], a device used in rehabilitation therapy for motor recovery after incomplete spinal cord injury. The time required for fitting this device for a new subject not exceed 15 min.

The Shape Memory Alloy (SMA) is a metallic alloy which has the property of recovering its original shape (the memorized shape) after being deformed when heated above the transformation temperature between a martensite phase (at low temperature) and an austenite phase (at high temperature). In this transformation, the total length can vary in the interval [3, 5]%. In the last decade, this type of actuator has sparked the interest of many researchers due to its promising characteristics: very good force/weight ratio, simplicity, low weight, and small size, which make them ideal to replace pneumatic, hydraulic or solenoid actuators. Between the disadvantages of this type of actuator, can be found: presents a elevate hysteresis, low energy efficiency and low actuation frequency. This type of actuator was successfully used in various application from biomedical field to robotics and automation [18].

This paper presents a wearable and portable exoskeleton (it is possible to use it at home, taking into account that a power supply unit is required) for elbow joint evaluation and rehabilitation therapy with two degrees of freedom (DOF) actuated by bioinspired Shape Memory Alloy (SMA) based actuators which are controlled for antagonistic movements. To the best of our knowledge, this is the first exoskeleton for elbow joint rehabilitation that relies on SMA actuators. Using this type of actuation, we propose an exoskeleton with a light weight (less than 1 Kg without power supply) and noiseless operation which increases the comfort of the patient. This device is a simple and inexpensive fabrication solution based on low cost components. These points can be viewed as important contributions of this work. An additional advantage is that the proposed system has a simple structure with an easy track for setup, considering that the installation time needs to be less than five minutes in this type of application. The exoskeleton makes it possible to offer intensive muscle reeducation and it enables the therapist to collect quantitative data on the nature and frequency of the movement patterns and the patient performance, aspects in which traditional one-and-one therapy is limited by time restrictions and staff availability.

This paper is divided in five sections. Section II presents the methodology of this work. It consists of presenting the biomechanical characteristics of the interest joint and a simulation of it, the actuator design, and the design of the rehabilitation device. In Section III, the control strategy and preliminary results are detailed. Sections IV and V show the discussion and the conclusions of this paper, respectively.

II. METHODS

This section presents a brief description of the biomechanical structure of the elbow and the biomechanical simulation of this joint, which is required to calculate the parameters that are needed in order to design the system. The last part shows the actuator, the proposed device design, and the hardware architecture.

A. BIOMECHANICS OF THE ELBOW

The elbow is a complex articulated joint composed by the humeroulnar and humeroradial joints (for the flexion-extension movement) and the proximal radioulnar articulation (for the pronation-supination movement). The flexion-extension movement, in the majority of the cases, has an angular range of movement between 0 and 150 degrees, but in the ADL the functional range is estimated between 30 and 120 degrees. In the pronation-supination movement, the averages are 71 degrees of pronation and 81 degrees of supination (Figure 1(a)). In ADL, the total range of pronation is approximately 50 degrees and for supination 50 degrees [19]. During the flexion-extension movement of the elbow joint, the center of rotation changes and this articulation cannot be truly represented as a simple hinge joint [19].

Many muscles are attached to the elbow joint. They can be in charge of the the elbow joint movement or their function can be related to the wrist and the hand. Different groups of muscles can be identified: flexor group composed of brachialis, biceps brachii, and brachioradialis; extensor group with triceps brachii and anconeus; muscles which act in the

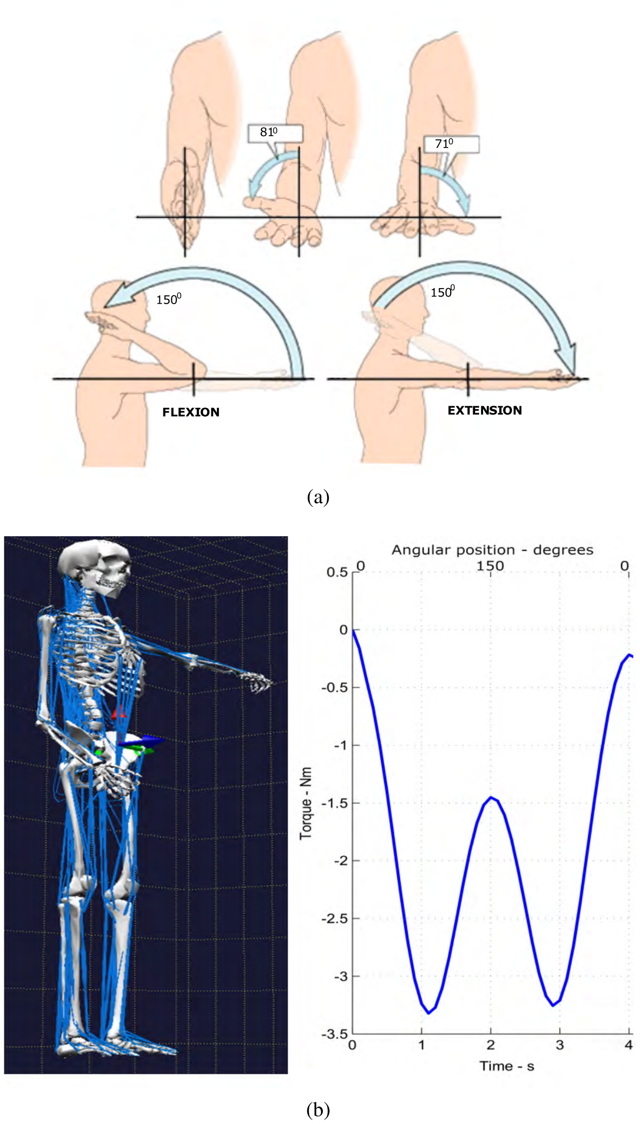


FIGURE 1. **(a) Normal range of motion for the elbow joint. (b) BoB simulator. Left: BoB simulator configured in the flexion-extension of the elbow joint. Right: Simulation results with the necessary torque in the elbow joint.**

rotation of the forearm pronator and the supinator; and group of muscles who act on the wrist and hand joints [20].

B. BIOMECHANICAL SIMULATION

Nowadays, in the development of any robotic device, simulation tools play an important role because it is possible to analyze the expected performance of the system designed prior to manufacture. To estimate the necessary torques in the joints for a specific patient, the Biomechanics of Bodies (BoB) simulation software [21] was used when compared with others biomechanical simulators like OpenSim [22] or AnyBody [23], this simulator is developed in Matlab/Simulink, which is an advantage because the control algorithm has been designed using the same software. In addition, a mechanical model of the exoskeleton can be imported and simulated. Finally, the learning curve of BoB is very short [24] and the biomechanical model contains more than 600 muscles. This software is capable of simulating the inverse dynamic behavior of the human body, receiving as inputs the height, the weight, and the motion joints. After simulation, the results or outputs represent the joints torques and the muscles forces.

In flexion-extension, a pilot study for this articulation was done configuring the simulator for a specific group of persons (patients) with the next parameters: weight of 70 Kg, height of 1.7 m, a trajectory in the right elbow joint between 0 and 150 degrees (where the 0 degrees is considered the maximum elbow extension), and a maximum frequency of movement equal to 0.25 Hz. In addition, in the right hand, a force of 20 N was applied. This force represents an approximation of the exoskeleton weight included in simulation. As can be seen in the simulation results (Fig. 1(b)), to complete the rehabilitation task successfully for the flexion-extension movement, a torque of approximately 3.5 Nm is necessary. This case assumes that the motor function is completely lost and all the force is produced by the exoskeleton.

The simulation software, BoB, can not simulate the second DOF (pronation-supination), and the torque of this joint has been fixed to 1 Nm. This value is above the torque required for this movement [25].

C. ACTUATOR DESIGN

The most common alloy is Nickel-Titanium, or Nitinol [26], but alloys of Nitinol with another metals can also be found [27]. The working principle of this type of actuator is based on the heating effect. In this work, the SMA is heated by means of the Joule effect and two transduction processes take place. First, electric energy is transformed into thermal energy thanks to the Joule effect. After that, the thermal energy is transformed into mechanical work. In function of the diameter and the alloy type, the actuator can exert different forces. The 0.51 mm diameter wire of Flexinol® [26] can exert a force of about 35.6 N (with a lifetime of tens of millions of cycles in these conditions). The SmartFlex® [27] wire with the same diameter can exert a maximum force of 118 N (with a lifetime of hundreds or a few thousand of cycles). Thanks to the good force/weight ratio (high force with a low weight) and flexible shape, this type of actuator is an ideal actuator for wearable devices [28].

In this work, the proposed actuator is formed by one or more SMA wires, Bowden cable, Polytetrafluoroethylene (PTFE) tube, and the terminal parts (Fig. 2):

- The Bowden cable is a mechanical flexible cable which consists of a flexible inner cable that forms a metal spiral and a flexible outer nylon sheath. This type of wire can guide the SMA actuators and transmit the force. In addition, the metal has the property of dissipating the heat, which is an interesting advantage during the recuperation of the initial position phase.

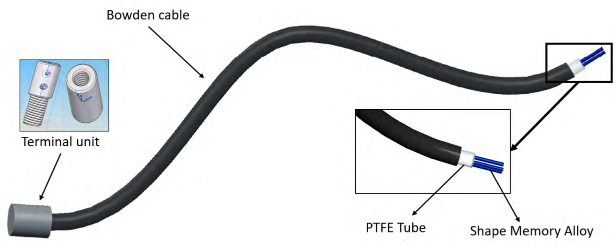


FIGURE 2. **Actuator design. Flexible SMA based actuator.**

TABLE 1. **SMA wires characteristics [26].**

Diameter Size (mm)	Force (N)	Cooling Time 70°C (s)	Cooling Time 90°C (s)
0.025	0.0089	0.18	0.15
0.038	0.02	0.24	0.2
0.050	0.36	0.4	0.3
0.076	0.80	0.8	0.7
0.100	1.43	1.1	0.9
0.130	2.23	1.6	1.4
0.150	3.21	2.0	1.7
0.200	5.70	3.2	2.7
0.250	8.91	5.4	4.5
0.310	12.80	8.1	6.8
0.380	22.50	10.5	8.8
0.510	35.60	16.8	14.0

- The PTFE tube can work with high temperatures, more than 250°C, it is an electrical insulator, and it does not cause frictions.
- The terminal units are used in one end to connect the actuator to the actuated system and, in the other one, to fix the SMA wires to the Bowden cable. They also serve as connectors for power supply (using the control signal). These units are formed by two pieces that can be screwed to each other to set the tension of the SMA wires. The total SMA wire tension range adjustment is 0.01m.

There is a relation between the SMA wire diameter, the force, and the cooling time (Table 1). In Table 1, the first column represents the diameter of the wire, the second column is the actuation force which guarantees a lifetime of tens millions of cycles, and the last two columns represent the cooling time for two type of wires with activation in 70°C and 90°C, respectively. According to the table and the objectives of the exoskeleton, it has been decided to work with 0.51 mm wires activated in 90°C because the maximum force is obtained with this diameter and the cooling time is lower when compared to the wire activated in 70°C.

If the SMA actuator is designed to operate with the configuration parameters shown in Table 1, the actuator lifetime can be tens of millions of cycles. If the actuator operates with forces higher than those specified, the lifetime drops to only a few thousand of cycles.

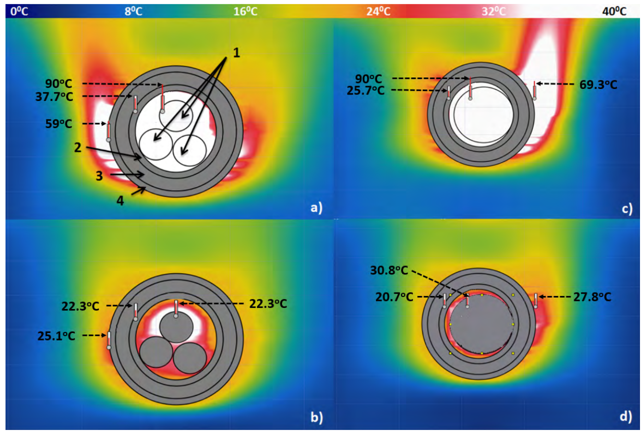


FIGURE 3. **Simulation of thermal convection for different setups of the actuator: 1 - SMA wires, 2 - PTFE tube, 3 - Metal part of the Bowden cable, 4 - Nylon part of the Bowden cable. a) 20 seconds with maximum actuation and three SMA wires. b) 10 seconds of cooling after 20 seconds with maximum actuation and three SMA wires. c) 20 seconds with maximum actuation and one SMA wire, d) 10 seconds of cooling after 20 seconds with maximum actuation and one SMA wire.**

If the actuator contains multiple SMA wires, it is necessary to decide between two different configurations: multiple SMA wires inside a single Bowden cable with PTFE tube or a Bowden cable with PTFE tube for each SMA wire. The configuration with parallel SMA wires and a single Bowden tube has some advantages: the size of actuator is more compact; the thermal convention between the SMA is better; the total energy that is consumed is reduced; and the actuator movement is accelerated. The disadvantage of this setup can be observed if the cooling stage is analyzed. The dissipation of thermal energy is slower, which results in a slower actuator recovery. This property can be deduced from the example presented in Fig. 3. This figure shows a simulation to study the thermal convection of the actuator. This simulation has been performed using the Energy2D software [29], according to properties of each component: geometry, thermal, optical, mechanical and source. Here were configured parameters like dimensions, temperature coefficient, reference temperature, thermal conductivity specific heat and density. Different situations are drawn: a) Three wires in the tube at 90°C during 20 seconds; b) Three wires after cooling during 10 seconds from 90°C to ambient temperature (20°C); c) and d) represent the same processes but with a single SMA wire inserted in a smaller Bowden cable with PTFE tube. Comparing b) and d), the actuator with three SMA wires has an approximate temperature of 50°C after 10 seconds, and the actuator with one SMA wire has an approximate temperature of 30°C. With these temperatures, according to the Dynalloy characteristics [26], the actuator with three SMA wires has a 0.3% approximate strain after 10 seconds, and the actuator with one SMA wire has a 0.1% approximate strain.

For patient safety, the actuators are not in direct contact with the human body, this are placed outside of the exoskeleton structure. They are covered by a protection tube and trapped in the back side of the human body. According to the simulation, if the actuators are contracted at maximum

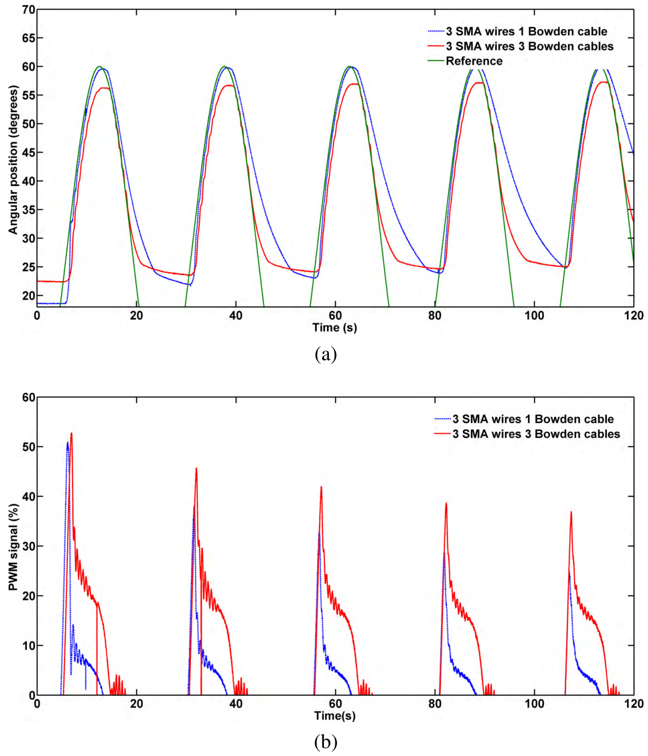


FIGURE 4. (a) Position response with sinusoidal reference and different configurations: three SMA wires in three different Bowden cables, and three SMA wires in a single Bowden cable. (b) The control signal (PWM) corresponding to the actuators response presented in Fig. 4(a).

force and displacement during 20 seconds, the external part of the Bowden cable has an approximate temperature of 60°C (Fig. 3 (a), which in direct contact (90°C) could be dangerous for the user. This type of actuation, maximum contraction during 20 seconds, is not probable in this type of rehabilitation tasks.

The objective of the following experiment is to compare both options to choose the most adequate one. The control strategy will be explained in Section III.

Fig. 4(a) presents the results of real tests with the two configurations (three SMA wires in three different Bowden cables or three SMA wires in a single Bowden cable). Both options were tested with the same control algorithm in a test bench that can simulate the elbow joint of the human body for a person of 70 kilograms. The initial position of the elbow joint is 20 degrees, and the reference follows a sinusoidal pattern with a 30 degrees amplitude and a 30 degrees bias.In Fig. 4 (a), the exoskeleton does not follow the position pattern below 20 degrees due to a mechanical restriction of the test bench.

As can be seen in Fig. 4(a), the configuration with three Bowden cables has a slower response in the heating stage. This is caused by its better heat dissipation. This effect can also be observed in the cooling stage, where this configuration has a lower recovery time. After some cycles the difference between both configurations in the cooling stage is more evident due to the heat accumulated in the Bowden cable.

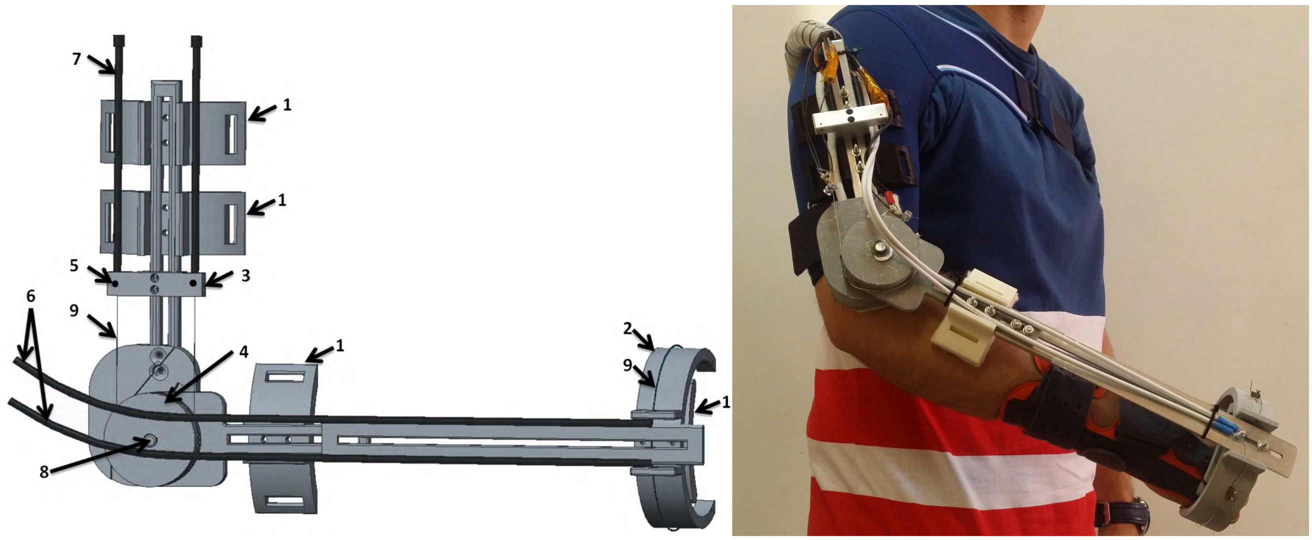
The corresponding control signals, PWM (Pulse With Modulation) currents, are given in Fig. 4(b). Although the peaks at the beginning are similar for both configurations (and the energy consumption, which is proportional to the PWM signal), the option with a single Bowden cable has a lower energy consumption during the displacement stage, due to the thermal convention between SMA wires. For this reason, the energy consumption is reduced and the PWM duty cycle presents a different amplitude. The amplitude of the PWM signal decrease over the time in both cases, due to the heat accumulation in the Bowden cable, the necessary heat to reach the reference temperature is bigger in the firsts cycles and less in the last ones.

According to this study, the option with three SMA wires in a single Bowden cable with PTFE tube has been chosen in this work.This setup has been selected because the reference signal is followed more accurately during the heating stage, is more compact and has a lower energy consumption, which makes this option more suitable for the tasks proposed in this paper. An additional advantage of this setup is that it is easier to have the same tension in the wires during the displacement (a different tension can cause the breakage of the wires) because all of them are linked to the same connector.

D. ELBOW EXOSKELETON STRUCTURE DESIGN

The mechanical design of the exoskeleton follows the concepts and requirements given in Sections II-A, II-B and II-C. The Computer Aided Design (CAD) model of the structure of the exoskeleton is displayed in Fig. 5(a).

For the flexion-extension movement, taking into account that the actuator presents a linear movement and, in the elbow joint, a rotation movement is needed, a 0.06 diameter pulley is introduced. Considering this diameter, the necessary torque (approximately 3.5 Nm), the desired range of movement between 0 and 120 degrees (ADL), and the force of the SMA wire, an actuator with three SMA wires of 1.5 m length is required. This means that, since each wire produces 35.6 N, the torque of the elbow joint is 3.204 Nm (in optimal conditions, but it can be easily considered that the torque is 3.5 Nm without affecting significantly the actuator lifetime). This torque can be obtained during tens of millions of cycles when each wire of SMA works with the characteristics presented in Table 1, without significant change in torque over time. Considering the decrease of lifetime when the actuator force is raised, if the maximum force of each cable is increased to 118 N [27], the torque in the elbow joint is 10.62 Nm, but the lifetime of the actuator is reduced to few thousands of cycles. Moreover, the actuator structure allows to easily insert another SMA wire to increase the total torque. In addition, it is possible to install a torsion spring, which is helpful for the flexion-extension movement (when only the flexion actuator is used and the extension movement is done with the aid of gravity and a spring). The torsion spring helps to recuperate the initial position of the actuators (extension movement) when the patient executes the rehabilitation task with the arm horizontal with the ground and the gravity does



(a) (b)

FIGURE 5. SMA exoskeleton design. (a) CAD structure: 1- attachment points, 2- fixed structure for supination-pronation, 3- actuator termination for Bowden tube, 4- pulley for linear to rotational transformation. 5- temperature sensors 6- supination-pronation actuators 7- flexion-extension actuators 8- absolute encoder 9- SMA wires. The forearm exoskeleton segment size from the center of rotation to the final (the connection point between the exoskeleton and human hand) is 0.4 m. This is the maximum size which can be adjusted to the patient forearm. The minimum forearm size which exoskeleton can be adjusted is 0.2m, displacing the piece which do the connection between the exoskeleton and human hand. The total arm exoskeleton segment size is 0.25 m and the position of the connection parts can be easy modified over this segment to adjust to the patient arm. (b) SMA elbow exoskeleton over human body.

not have effect on the elbow joint in flexion-extension. In the extension movement, the necessary torque depends of the position of the arm (the gravity force) and the torsion spring force. In function of this, the necessary torque for the forearm extension is less than 3.5 Nm and an actuator based on two SMA wires is proposed.

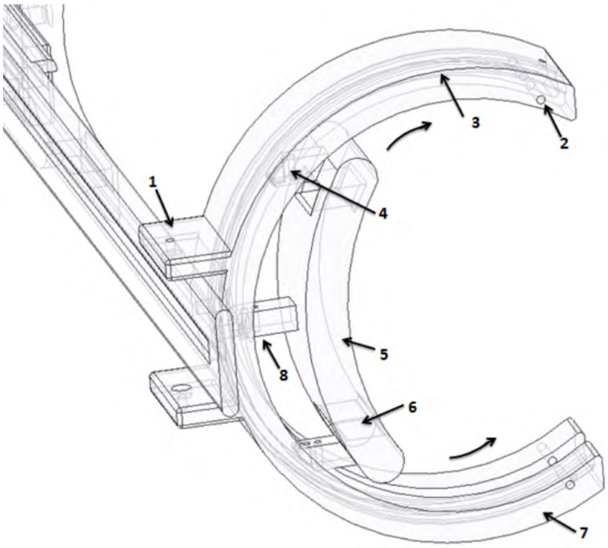
For the pronation-supination movement, the CAD can be observed in Fig. 6(a) and the real device is shown in Fig. 6(b). This design consists of a fixed part connected to the forearm, and a sliding part connected to the hand. The actuation of the sliding part, with two antagonist actuators, generates the pronation-supination movement of the forearm. According to the proposed mechanism for the fixed part, with an internal diameter of 0.1 m, two SMA-based actuators are required, each one with one SMA wire of 2 m length. This configuration was chosen according to the necessary torque in the pronation-supination movement (approximately 1Nm) and the linear displacement requirement (0.08 m). With this configuration, the forearm can be moved 50 degrees in pronation and 50 degrees in supination, representing the necessary movement of the ADL. Due to its flexibility and low weight, the actuator can be adjusted according to the human body's shape and the total length of the actuator is not a concern. The movement range and the patient comfort zone are not affected when the length is increased. A summary of the system configuration depending on the movement can be seen in Table 2.

The exoskeleton is made from simple parts which give the possibility of easy assembly. Different configurations can be defined depending on the patient. Each component

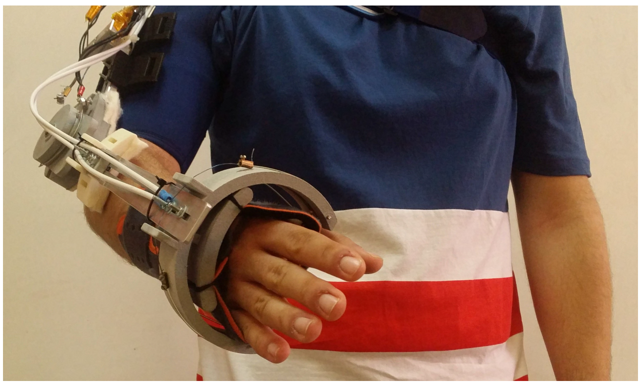
TABLE 2. Exoskeleton actuators.

Movement	SMA wires	Maximum force [N]	Length [m]	Weight [kg]
Flexion	3	354	1.5	0.16
Extension	2	236	1.5	0.15
Pronation	1	118	2	0.1
Supination	1	118	2	0.1

can be easily made with a 3D printer (layered manufacturing technology, material aluminum with polyamides). The exoskeleton has four attachment points with the human body, connected to the arm (two of them), the forearm, and the hand (Fig. 5(a)). The attachment points are adjustable in function of the patient. Arm and forearm length are taken into account to align the rotation centers of the device and the elbow. The hand connector presents one DOF, which gives the possibility of pronation-supination of the forearm. For the safety of the patient, the exoskeleton movement is mechanically limited between 0 and 150 degrees. In order to increase the comfort, all internal parts in contact with the patient are covered with a soft hypoallergenic material, wool adhesive hypoallergenic sheet manufactured by Quadreny Pax, S.A.. Comparing with the current solutions, due to the lack of gears and motors in the mechanism, the proposed rehabilitation device presents a light weight. The whole structure with the actuators weighs less than 1 Kg. A 960W DIN Rail Power Supply (24Vdc/40A) manufactured by PULS Dimension is used to provide the necessary energy to the actuators. The weight of the Power Supply unit is 1.9kg. In addition, it presents a noiseless operation characteristic, which increases the comfort of the



(a)



(b)

FIGURE 6. Exoskeleton pronation-supination parts. (a) CAD structure for the pronation-supination parts. 1 - actuator termination for Bowden cable, 2 - shaft for pulley, 3 - canal slip, 4 - terminals for traction cable hold, 5 - sliding part, 6 - attachment point (to the hand through a belt), 7 - fixed part, 8 - sliding point. (b) real design.

patient in the rehabilitation process. The final version of the exoskeleton can be seen in Fig. 5(b).

E. ELECTRONIC HARDWARE

The electronic hardware is composed from the power electronics, the controller and the present sensors in this device. The power electronics is based on a MOSFET transistor (STMicroelectronics STP310N10F7), which works as a commutation circuit and amplifies the control signal (PWM) generated by the controller. This device is connected to the terminal units of the SMA - based actuator.

The controller is a 32 bits microcontroller STM32F4 from STMicroelectronics®, which can be fully programmed with Matlab/Simulink® [30]. With the electronics, the control hardware architecture is capable of managing16 distinct actuators (each actuator with one or more SMA wires). In this case, for the elbow joint, only 4 controllers are needed for flexion, extension, pronation, and supination (one for each movement).

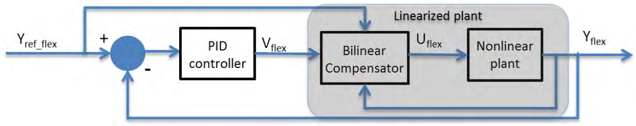


FIGURE 7. BPID control scheme. BPID control scheme [31] (taken and adapted from [32]). Y_{ref_flex} is the desired angular position, Y_{flex} is the position sensor signal, V_{flex} is the control signal generated by the PID controller and the U_{flex} is the control signal rectified by the bilinear term.

The structure of the rehabilitation device includes position sensors and temperature sensors. The position sensor is placed in the shaft of the exoskeleton (pulley for flexion-extension). This sensor is a Hall effect encoder with a resolution of 0.0879 degrees. The temperature sensors are placed in the terminal of the actuator to measure the temperature of the SMA wires, parameter that is required in the control loop. All the electronics used in this project is based on low-cost components.

III. CONTROL STRATEGY AND PRELIMINARY RESULTS

The control strategy proposed in this work relies on a simple four-term Bilinear PID (BPID) controller, control strategy was successfully applied in [31] to control a single SMA wire. The BPID controller is a combination of a standard linear PID controller cascaded with a bilinear compensator (Fig.7). The architecture relies on the structure proposed by Martineau *et al.* [32]. Depending on the desired therapy, the position reference and the control performance can be chosen to meet different requirements:

- flexion movement and recuperation of the initial position (extension movement of the elbow joint) with the aid of the gravity force and the torsion spring;
- antagonistic movements, two actuators for flexion and extension, respectively;
- reading sensors data (without actuation), necessary for evaluation and diagnosis of the patient.

The entire experimental test was performed in the same condition of the simulation set-up but with different frequency of movement. Each strategy is explained in the following sections.

The pronation-supination movement is governed by two SMA wires that produce the antagonistic movements. This offers the possibility to work as an active or passive device (when the device is not actuated and it only makes the data acquisition).

A. FLEXION MOVEMENT

The main difficulty when controlling SMA - based materials is their saturated hysteretic behavior, which appears during martensite-austenite and austenite-martensite transformations. This introduces in the system nonlinear behaviors, which makes it difficult to develop control algorithms for this type of actuator. Nonlinear control algorithms are needed, which are more difficult to implement and calibrate when compared to linear controllers.

TABLE 3. BPID controller gains.

Gain	Kp	Kd	Ki	Kb
Value	10	4	0	2

Moreover, the problem is more complicated in this system because several SMA wires mounted in parallel have to be controlled. In this case, various SMA wires are mounted in parallel in the same Bowden cable. They are fixed with the aid of the terminal units, which do not guarantee the same tension in each wire. Instead of controlling one wire, a sum of nonlinear models with different tensions is controlled with a single controller in this case. Different tensions between cables cause one SMA wire to support more force (when compared to the others), especially at the beginning when the actuators are in their initial positions. If the difference between them is significant, the breakage of the wire is probable.

The nonlinearities of the plant limit the performance of the control loop and, applying this type of control architecture, an important advantage was obtained. In this cascaded structure, the secondary loop (bilinear term) is capable of compensating the dominant perturbation of the system. This control strategy is proposed for the flexion movement of the elbow joint. The same approach will be followed for the other movements. The reference signal is the desired angular position (Y_{ref_flex}) and the system feedback is represented by the position sensor signal (Y_{flex}), which is the real angular position of the exoskeleton.

The gains of the BPID controller were experimentally set by changing the gain values and observing the actuator response. The exoskeleton was installed on a test bench that can simulate the weight of the forearm with one DOF for a person with a weight of 70 Kg. The gains of the BPID are shown in Table 3.

The state-space representation of a continuous single-input single output (SISO) bilinear system is given by:

$$\dot{x}(t) = Ax(t) + bu(t) + u(t)Nx(t), \qquad (1)$$

$$y(t) = Cx(t), \qquad (2)$$

where $x \in \Re^n$ is the state vector, $u(t)$ is the input, A is a $n \times n$ matrix of real values, b is a $n \times 1$ vector of real values, C is a $1 \times n$ vector of real values, and N is a $n \times n$ matrix of real constants (comprising the bilinear coefficients).

The formula of the compensator that is introduced in the bilinear controller is:

$$\frac{U_{flex}(z)}{V_{flex}(z)} = \frac{1 + K_b Y_{ref\_flex}(z)}{1 + K_b z^{-1} Y_{flex}(z)}, \qquad (3)$$

where $Y_{ref}(z)$ is the reference output at which the PID controller was tuned. This term compensates the nonlinearities of the plant. More information about how this formula is deduced can be found in [31] and [32].

The PID controller is used to send a PWM current $I(z)$ to the actuator according to the following equation:

$$I(z) = [K_p + \frac{K_i}{1 - z^{-1}} + K_d(1 - z^{-1})]E(z), \qquad (4)$$

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.

The response of the controlled system provided by the position sensors was compared to the desired reference. Two responses were analyzed: tracking a step and a sinusoidal reference.

1) STEP RESPONSE

Fig. 8(a) shows the angular position reference and the output when the device is mounted in the test bench. It can be observed that the output follows the reference (the steady-state error is zero) and the system presents an overdamped response. The time to go from 0 to approximately 120 degrees is less than 10 seconds, and the time required to recuperate the initial position is approximately 30 seconds (considering that it is not necessary to get to 0 degrees and is enough to move between 30 and 120 degrees in ADL). In this case, only the flexion actuator was activated and the initial position was recuperated with the aid of the gravity force and the torsion spring placed in the shaft of the exoskeleton. Flexion time can be minimized to changing the controller gains (Fig. 8(a)), but an aggressive control signal reduces the lifetime of the actuator). However, the time of the extension movement is dependent on the recuperation force and the ambient conditions (temperature). It has to be said that this example is an extreme case because the actuator varies from the initial position in martensite phase (at low temperature) to the maximum position in austenite phase (at high temperature). If the position reference does not cover the maximum range of the actuator and the austenite phase is not reached, the time of recuperation remarkably decreases.

The movement of the exoskeleton is relatively slow in the extension movement and it could only be used in slow (when compared to ADL movements) rehabilitation tasks, especially during the first phase of the rehabilitation process. A solution could be to increase the total length of the actuator. In this case, the same displacement could be obtained without the maximum range and the recuperation would be faster. This would have an effect on the mechanical structure of the exoskeleton and some parts would need to be adapted.

2) SINUSOIDAL RESPONSE

The second test highlights the behavior of the exoskeleton with a sinusoidal reference signal (Fig. 8(b)). In this case, the angular position reference is a sinusoidal signal with an amplitude of 80 degrees and a frequency of 0.2 rad/sec. In this case the test was done over a healthy subject in standing position defined based on the sagittal plane. With the same controller gains, the exoskeleton response is capable of tracking with accuracy the reference signal during the flexion

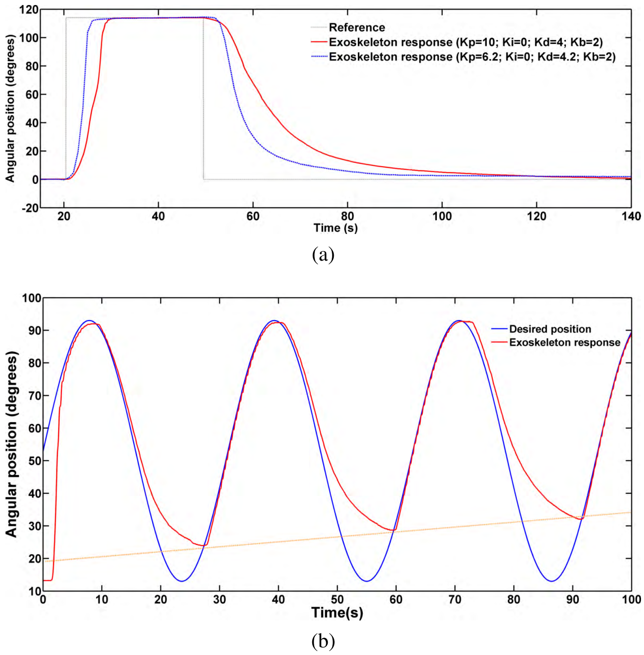


FIGURE 8. Exoskeleton position response to a: (a) step reference, (b) sinusoidal reference. The orange line represent the error increment through the heat accumulation.

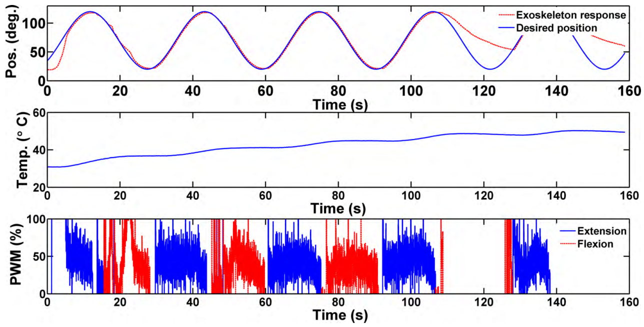


FIGURE 9. Desired position and exoskeleton angular response in antagonist movement, Bowden temperature and control signal.

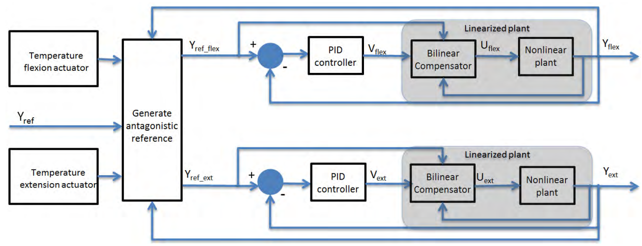


FIGURE 10. BPID control scheme. Antagonist control scheme with two parallel four-term BPID controllers.

movement. In the extension movement, due to the lack of control (no signal is sent) and the capacity (of the actuator) to recuperate the initial position in the cooling phase, the response presents an elevated error. Besides, this error increases with working time. Due to the frequency of the input signal, the actuator does not have time to dissipate the accumulated heat. According to the actuator response detailed in Section III-A1, the system needs approximately 30 seconds to dissipate the accumulated heat. This means that the sinusoidal cycle needs a frequency of 0.046 rad/sec to have an optimal performance. The increase of error shows a linear behavior, and it is represented in Fig. 8(b) with an orange dashed line.

B. ANTAGONISTIC MOVEMENTS

In the antagonistic movements layout, two actuators are configured in the elbow joint: one of them with three SMA wires for the elbow flexion, and the other one with two SMA wires for the elbow extension. Through this design, it is possible to abandon the use of the torsion spring in the elbow joint because the extension movement is made by the actuator. The initial setup includes the torsion spring in the elbow exoskeleton articulation. The next tests have been made with the extension and flexion actuators with sames parameters used in simulation.

Considering the operating principle of this type of actuators presented in Section II-C, it is necessary to introduce temperature sensors because the information provided by these sensors is used in the control algorithm. These sensors (MLX90614) are placed in the terminals of the actuators to measure the temperature of the Bowden tube in real time. The control signal takes into account the temperature of each actuator to avoid the breakage of the wires. Switching control signals from one actuator to another can lead to breakage if the temperature of the wires is not considered. The constraint that is introduced in the model is that, to activate an actuator, the temperature of the antagonist actuator needs to be lower than a value that is fixed empirically (48°C). For example, if the flexion wires are activated with a temperature of approximately 90°C and (suddenly) the control algorithm switches to activate the extension wires with an elevated control signal, the temperature constraint interrupts the signal to avoid breakage. When the Bowden tube temperature is higher then 48°C, the extension movement actuator is not actuated to avoid the breakage. More details about this mechanism will be seen below in the analysis presented in the Fig. 9.

The control scheme in this case is based on two BPID controllers in parallel (Fig. 10). The exoskeleton movement is still controlled in angular position.

The control algorithm receives only the pattern of reference, which is the desired angular position for the elbow joint. This reference, depending on the actual position (the feedback signal from the position sensor), generates two reference signals for the flexion and the extension movements, respectively. The control signal of one of these two references is fixed to zero, and the other one represents the positive difference between the desired reference and the actual position. The temperature condition intervenes in the control algorithm when the temperature of the antagonist actuator (Bowden tube) is higher than 48°C (interrupting the control signal). Because of the cooling time and, in order to obtain a continuous movement in the antagonist control approach, it is recommended to use sinusoidal references. For the step reference, a delay equal to the time required to cool the wires may occur. This can be annoying in the rehabilitation therapy.

Fig. 9 displays the response of the exoskeleton in antagonist mode when the pattern of reference is represented by a position sinusoidal signal with an amplitude of 100 degrees and a frequency of 0.2 rad/sec. The antagonist controller achieves a high accuracy when tracking the position reference. Compared to the flexion movement controller presented in Section *Sinusoidal response*, the error in the extension movement is drastically reduced. Moreover, using this type of controller, the rehabilitation therapy does not depend on the position of the forearm, it does not need the gravity force, and the spring torsion force for the extension movement is not required.

The control signals corresponding to the two BPID controllers can be seen in Fig. 9. From the general reference (the desired angular position of the exoskeleton), two distinct references are generated for the flexion and the extension movements, respectively. The control signals (PWM) of these references are activated alternatively, the blue signal corresponding to the flexion movement and the signal dashed line corresponding to the extension movement.

The exoskeleton follows with accuracy the desired reference in the first three cycles and in all the flexion movements. The interruption of the extension actuator control signal (the control signals corresponding to the intervals 110-130 seconds and 140 - 160 seconds is 0) for the extension movement is due to the increase of the actuator temperature. This interruption is automatically activated if the temperature of the extension actuator is higher than 48°C to avoid the wires breakage. If the temperature of this actuator is below than this value, the control algorithm automatically activate the extension actuator involved them in the exoskeleton movement in function of the desired reference.

An additional experiment in which the frequency is increased to 0.4 rad/sec (two times the previous one) and cooling with airflow is included (Fig. 11 (a)). Here when the flexion actuator was active a airflow through the extensor Bowden tube was introduced and vice versa.

C. READING SENSORS DATA

In the passive mode, the exoskeleton is not actuated and it only reads the sensor data. In this mode, the actuator control is not activated and the exoskeleton only needs the connection with the PC for microcontroller sensors power supply and data acquisition (the exoskeleton is not actuated and only the electronics is powered). Without control, the exoskeleton joints moves freely. Some tests in the passive mode have been performed with a healthy subject. After the exoskeleton was fixed over the body, the subject was asked to do few flexions – extensions movements of the elbow joint. With the aid of the sensors the angular data position of the elbow joint was stored, and processed to obtain the angular velocity and estimated torque.The data acquisition from sensors can be seen in Fig. 11(b).

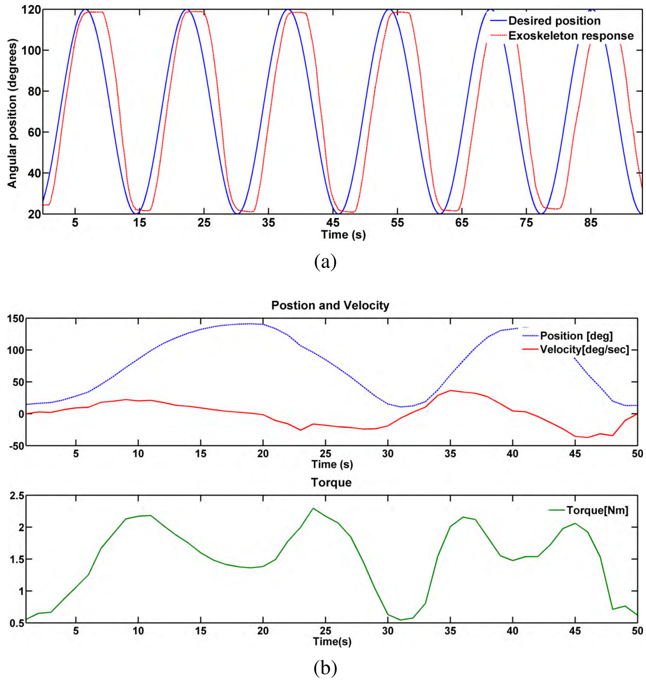


FIGURE 11. **(a) Desired position and exoskeleton angular response when the frequency is increased and cooling with airflow is included (b) Data acquisition and processing: position, velocity and torque.**

After data processing, the software returns the position of the elbow joint in degrees, the velocity in degrees/second, and the estimated torque in the elbow joint in Nm. The estimated torque has been calculated using the biomechanical equations for the human body for the elbow motion (position, velocity and acceleration) and the subject weight and height. These formulas are based on [33] and [34]. The estimated torque considers that the human body is in an anatomical position and it only moves the elbow in flexion-extension.

IV. DISCUSSION

Throughout the development of this rehabilitation device, and for a good acceptance of the patients and the therapeutic staff, we have collaborated with the therapists of the Rey Juan Carlos University of Madrid, Spain. From the initial design to this prototype, a number of changes in the structure have been made to improve the comfort of the patient during the rehabilitation therapy and, at the same time, to obtain the data that the therapeutic staff requires when evaluating a patient. In terms of structure, the device is made of segments which can be easily set according to the patient. The exoskeleton structure, actuators and electronics was made with a low cost- cost components which permitted to reduce substantially the fabrication cost of this device. Also, due to the actuators characteristics the device presents a noiseless operation, which increase the acceptance possibility of it by the patients. In the future, the possibility to connect them to similar rehabilitation devices for the shoulder (preliminary design presented in [35]) or the wrist (presented in [36]) will be studied.

Analyzing the preliminary feedback from the therapeutic staff about the first prototype, they highlighted the light weight when compared to the current solutions (with which they have interacted). Also, comparing this exoskeleton characteristic with the currently solutions (some of them presented in Section I), the majority of them are stationary devices, actuated with conventional actuators which presents a very high weight. In the case of portable devices, this present less weight (ones of them similar with the proposed device), but often the torque in the articulations is quite limited. They also concluded that it has a good setup time, important because if it takes longer than five minutes it is very likely that therapists will abandon the use of the device.

In terms of patient assessment, the exoskeleton can be used in the passive mode to measure the angular position, the velocity and, with the aid of the torsion spring, the estimate of the force that can be done in the flexion of the elbow. Thanks to the bearing placed in the elbow shaft the friction is considered negligible.

As can be seen in Section III, the rehabilitation device is ideal for slow movements which do not exceed the frequency of 0.2 rad/sec; otherwise, after some operating cycles, the actuator needs to cool down (it may take about a minute, depending on the ambient conditions). However, the number of operating cycles without interruptions caused by the deterioration of the wires is considered sufficient. Due to this speed limitation, the exoskeleton is adequate for the slow rehabilitation therapy's that is common in the early stage after the disorder happen. Here, slowly repetitive rehabilitation movements are done to avoid pains and involuntary muscle contraction. The second limitation of this system is the number of continues operating cycles, which depend of the patient characteristics: weight and disorder (if presents or not muscular activity). This limitation is caused by the actuator temperature increasing which oblige to stop the system to cool them. To maintain the patient involved in the rehabilitation therapy, during the time which the flexion extension actuator cool the therapy of prono-supination can be done. In parallel with this work, our research group is working on alternative cooling solutions to accelerate the ''recovery'' time of the actuator.

The total range of movement of the exoskeleton with the current configuration varies from 0 to 120 degrees, which is considered an adequate interval to perform ADL. This range of movement can be easily expanded to 150 degrees only by changing the length of actuators. Within this range, the exoskeleton is capable to track the reference with an error that does not exceed four degrees in antagonist set up. In flexion movement, only the flexion movement can be controlled, and a large error can be seen in the extension movement. In function of the muscular group that is going to be trained, it is possible to choose between these two types of controllers.

The exoskeleton has been tested in a test bench capable of simulating the forearm weight of a 70 Kg person (additional weight can also be added). Besides, it has been tested in the laboratory with the staff, using both the passive and the actuated modes.

V. CONCLUSION

In the last decade, the increase of the number of persons with physical disorders, either from CVA, SCI, or different types of motor neurons disorders, has become a matter of concern. A significant portion of these disorders can be recuperated with the aid of rehabilitation therapies. These therapies can be more beneficial for the patient if they are made with the aid of rehabilitation devices.

This work presents the first wearable elbow exoskeleton for evaluation and rehabilitation therapies that is actuated with SMA - based actuators. Using this type of bioinspired actuator technologies, capable of actuating in an antagonist mode, the weight of the exoskeleton is drastically reduced (less than 1 Kg). Moreover, this device achieves a noiseless operation, which increases the comfort of the patient.

The exoskeleton exhibits a simple structure, adaptable in function of the patient, which permits an easy installation. The required time is approximately five minutes. It is considered as a simple and inexpensive fabrication solution; most components can be produced by 3D printing technology and the electronics and actuators are based on low-cost components. It can be a solution for hospitals which do not have the potential to buy expensive rehabilitation products or (why not) it can be purchased by patients to be used at home.

The rehabilitation device can work in a passive mode, only for data acquisition without activating the actuators, and in active mode in flexion or antagonist configuration. The antagonist controller shows high accuracy when tracking the position reference, eliminating the error caused by the ''recovering'' time needed by the actuator.

ACKNOWLEDGMENT

The authors are grateful for the collaboration of the LAMBECOM research group, of Rey Juan Carlos University of Madrid, Spain, in defining the design requirements and their participation in the evaluation of preliminary designs. Moreover, our acknowledgment to Ph.D. James Shippen of Coventry University, UK for his help with the BoB toolbox.

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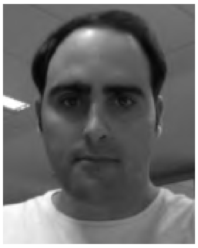

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