Modelling, design, and construction of a wrist rehabilitation exoskeleton

Modelado, diseño y construcción de un exoesqueleto para rehabilitación de la muñeca

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***Abstract*—This work presents the modelling, design, construction, and control of a wrist joint flexion/extension and abduction/adduction rehabilitation exoskeleton. The dynamic models of the wrist movements are obtained using Euler-Lagrange formulation and are built in Simulink of MATLAB in conjunction with a PID closed-loop control representing the human natural neuromusculoskeletal control. Simulations are carried out to estimate the joint torque required to produce the functional wrist movements in an average Colombian adult. The exoskeleton is designed in SolidWorks CAD software, built through 3D printing in polylactic acid (PLA), powered by two on-board servomotors, and controlled by an Arduino UNO board that establishes communication with an Android mobile app developed in MIT App Inventor for entering the rehabilitation therapy parameters. The result of this work is a lightweight exoskeleton with a total mass of 0.64 [kg] including servomotors, microcontroller, and batteries, with the ability to be used in telerehabilitation practices, guaranteeing angular displacement tracking errors under 10%.**

***Index Terms*—Arduino, control, Euler-Lagrange, MIT App Inventor, model, radiocarpal joint, rehabilitation robotics, Simulink, wearable robotics.**

***Resumen*—Este trabajo presenta el modelado, diseño, construcción y control de un exoesqueleto para rehabilitación de la flexión/extensión y abducción/aducción de la articulación de la muñeca. Los modelos dinámicos de los movimientos de la muñeca se obtienen por medio de la formulación de Euler-Lagrange, y se construyen en Simulink de MATLAB junto con un control PID en lazo cerrado que representa el control natural neuromusculoesquelético del humano. Se realizan simulaciones para estimar el torque requerido en la articulación para producir los movimientos funcionales de la muñeca en un adulto promedio colombiano. El exoesqueleto es diseñado en el software CAD SolidWorks, construido a través de impresión 3D en ácido poliláctico (PLA), accionado por dos servomotores, y controlado por una tarjeta Arduino UNO que establece comunicación con un aplicativo móvil Android desarrollado en MIT App Inventor para el ingreso de los parámetros de la terapia de rehabilitación. El resultado de este trabajo es un exoesqueleto liviano con una masa total de 0.64 [kg] incluyendo servomotores, microcontrolador y baterías, con la capacidad de ser usado para prácticas de telerehabilitación, garantizando seguimiento del desplazamiento angular con errores por debajo del 10%.**

***Palabras claves*—Arduino, articulación radiocarpiana, control, Euler-Lagrange, MIT App Inventor, modelo, robótica de rehabilitación, robótica vestible, Simulink.**

I. Introduction

THE wrist joint is the anatomical area that establishes the union between the forearm and hand, constituted by the distal metaepiphyseal parts of the forearm bones (radius and ulna), and the carpus bones [1]. Its structural characteristics allow the execution of a large number of movements (flexion/extension, abduction/adduction or radial/ulnar deviation, pronation/supination, and circumduction) with great ranges of motion (ROM), while the ligament network favors the stability of the joint complex [2].

The wrist, in conjunction with the hand and fingers, plays a fundamental role in daily activities such as grasping tasks. However, its mobility and stability are significantly affected by injuries, sprains, fractures, and some neurological and musculoskeletal disorders, causing partial or total incapacity to perform grasping tasks autonomously. As an example, distal radius fracture, also called wrist fracture, is one the most common fractures in children and adults, especially women, and its causes range from sports injuries to age-related disorders such as osteoporosis [1].

Exoskeletons have a great potential for application in rehabilitation of wrist injuries, constituting as a technological support tool for physicians, physiotherapists, and traditional rehabilitation practices focused on the manual execution of repetitive movements to recover the normal and functional ROM of the patient joint [3]. Exoskeletons allow the execution of repetitive movements with adjustable values established by the health specialist, such as ROM, number of repetitions, and speed of the movement.

Dynamic modeling is considered the first step towards exoskeleton design and control, since it allows the evaluation of joint torques during the execution of desired movements. Serbest *et al.* [4] developed a dynamic model of the hand in SimMechanics to estimate joint torques of the wrist, metacarpophalangeal, and interphalangeal joints during

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flexion/extension and abduction/adduction. The model allowed customized analysis for individual anthropometric data by changing the parameters of the SimMechanics blocks and is intended to be used in the design of a hand assistive and rehabilitation device. Mansour *et al.* [5] worked on a kinematic model of the human upper extremity for the determination of joint torques in the wrist, elbow, and shoulder. The model was implemented in COSMOS/Motion software of SolidWorks, where the limbs were considered as rigid solids, and the torques were calculated through numerical simulations given input motions and inertial parameters of the solids. Agarana *et al.* [6] developed a model of the human arm (upper arm, forearm, and hand) as a dynamic triple pendulum system using Euler-Lagrange formulation and implemented the differential equations of motion in Maple software. Peña-Pitarch *et al.* [7] proposed a 25 degree-of-freedom (DOF) hand skeletal model derived from Denavit-Hartenberg method, forward and inverse kinematic analysis, and Jacobian rank deficiency method. The model allowed variable anthropometric data and intuitive visualization of workspace, and it is intended to estimate joint torques in daily activities such as grasping tasks.

Wrist rehabilitation devices of previous works consist of parallel and wearable robots powered by DC motors, elastic, and pneumatic actuators. Mazia *et al.* [8] developed the IIT-Wrist, a three DOF parallel robot for neuroscience study and rehabilitation of wrist flexion/extension, abduction/adduction, and pronation/supination, powered by three DC motors. Gupta *et al.* [9] designed the RiceWrist, a three DOF robot to provide rehabilitation of motor skills and reaching movements of the wrist. The robot was powered by brushless DC motors with an angular position PID control and allowed execution of wrist movements with fast response time, little overshoot, and small steady-state errors, in a compact parallel mechanism with low friction, zero backlash and high stiffness. Torres-Sarmiento *et al.* [10] worked on a three DOF parallel robot for wrist motor rehabilitation in patients with cerebrovascular accident (CVA). The exoskeleton was powered by DC motors, allowed execution of flexion/extension, abduction/adduction, and pronation/supination, and implemented an ergonomic joystick for holding the hand to the robot, to resemble rehabilitation processes performed by human therapists. Serrano *et al.* [11] presented a two DOF rehabilitation exoskeleton for the wrist flexion/extension and abduction/adduction, powered by shape memory alloy (SMA) actuators based on Nitinol. SMA actuators recover their original shape (memorized shape) after being deformed when they are heated above the transformation temperature between a martensite phase (low temperature) and an austenite phase (high temperature). The exoskeleton presented low weight (less than 1 [kg]), low fabrication costs (approximately 1000 euros including the device and electronics) and noiseless operation. Allington *et al.* [12] designed SUE, a lightweight (0.56 [kg]) two DOF pneumatically actuated exoskeleton to assist forearm pronation/supination and wrist flexion/extension in patients who suffered CVA. The authors used pneumatic technology due to its large and compliant forces. However, effective use of pneumatics required careful design considerations, such as kinematic design to place the actuators on the outside of the arm, minimization of the nonlinear effects of seal stiction by appropriate cylinder sizing and use of four solenoid valves per cylinder to reduce friction and improve energy efficiency.

This work presents the modelling, design, construction, and control of a flexion/extension and abduction/adduction wrist joint rehabilitation exoskeleton. The paper is organized as follows: section II describes the modelling of the wrist movements using Euler-Lagrange formulation, and the implementation of the dynamic models in Simulink with a PID control representing the human neuromusculoskeletal control. Simulations are carried out to estimate the joint torque required for the wrist functional ROMs. Section III shows the design of the exoskeleton in SolidWorks CAD software, the selection of the actuators, and the construction of the exoskeleton elements through 3D printing in polylactic acid (PLA). The electronic circuit and control system is exposed in section IV, with the development of an Android mobile app designed in MIT App Inventor for entering the rehabilitation therapy parameters. Finally, section V presents angular displacement tracking performance tests of the exoskeleton for different ROMs, and the results are evaluated in terms of the relative maximum error (RME), to present the final conclusions of the work in section VI.

II. Dynamic models

The wrist joint flexion/extension and abduction/adduction dynamic models are obtained through Euler-Lagrange formulation considering the system shown in Fig. 1, where the hand is modeled as a rigid bar of length L, mass m, and proximal gravity center l, the origin of the coordinate system is fixed at the wrist, and the hand is extended or abducted at an angle θ.

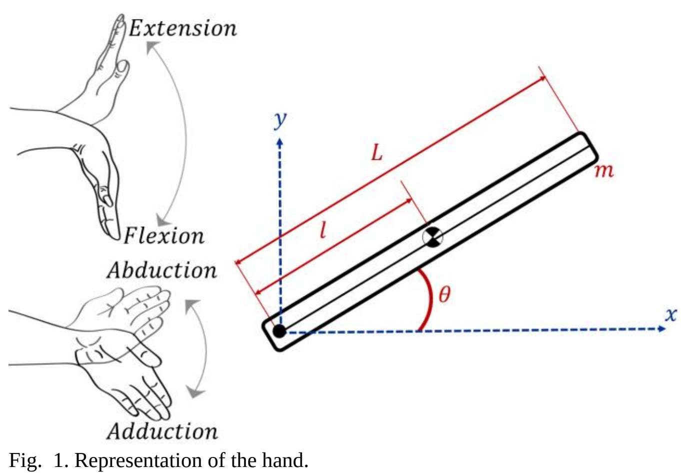

Fig. 1. Representation of the hand.

The Lagrangian L is defined as the difference between kinetic energy T and potential energy V of the system:

$$L = T - V \quad (1)$$

The kinetic energy of the system under consideration is established in (2), where J is the moment of inertia and $\dot{\theta}$ the angular velocity of the hand, and the potential energy is defined as in (3).

$$T = \frac{1}{2}ml^2\dot{\theta}^2 + \frac{1}{2}J\dot{\theta} \quad (2)$$

$$V = mglsin\theta \quad (3)$$

Substituting (2) and (3) into the Lagrangian definition (1) results in (4).

$$L = \frac{1}{2}ml^2\dot{\theta}^2 + \frac{1}{2}J\dot{\theta} - mglsin\theta \quad (4)$$

Euler-Lagrange formulation is defined as in (5), where k are the system's DOF, q_k the set of generalized coordinates, and Q_k the set of external (non-conservative) forces.

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_k}\right) - \frac{d}{dt}\left(\frac{\partial L}{\partial q_k}\right) = Q_k \quad (5)$$

The exoskeleton considered in this work has two DOF related to the wrist flexion/extension and abduction/adduction. However, since this movements are separately executed in rehabilitation therapies, then Euler-Lagrange equation is considered for only one DOF related to the rotation around the wrist joint. External forces consist of the torque T and the viscous damping at the joint with a damping coefficient b. Considering this, the Euler-Lagrange formulation turns into:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}}\right) - \frac{d}{dt}\left(\frac{\partial L}{\partial \theta}\right) = T - b\dot{\theta} \quad (6)$$

Lagrangian derivates of (6) are solved resulting in the non-linear second-order differential dynamic equation (7) that describes the dynamics of the wrist flexion/extension and abduction/adduction.

$$ml^2\ddot{\theta} + J\ddot{\theta} + mglcos\theta = T - b\dot{\theta} \quad (7)$$

Equation (7) is solved for the highest order derivate $\ddot{\theta}$ to build the dynamic models in Simulink resulting in (8).

$$\ddot{\theta} = \frac{1}{ml^2 + J}\left[T - b\dot{\theta} - mglcos\theta\right] \quad (8)$$

Wrist dynamic models in Simulink are shown in Fig. 2 and 3 for flexion/extension and abduction/adduction, respectively. The input to the models is the joint torque, and the outputs are the angular displacement, angular velocity, and angular acceleration of the hand in units of $[rad]$, $[rad/s]$ and $[rad/s^2]$ respectively. Signal saturators are installed on the angular displacement to restrict the ROMs of the different movements according to the normal values reported in literature [2] and summarized in Table I. These saturators are applied through SPDT (single pole, double throw) switches, which are automatically commutated by using a sign function block depending on the movement performed by the wrist.

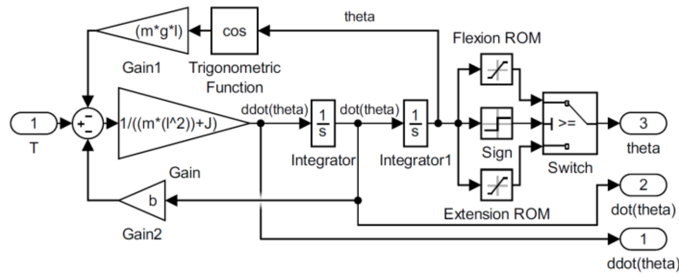

Fig. 2. Wrist flexion/extension dynamic model in Simulink.

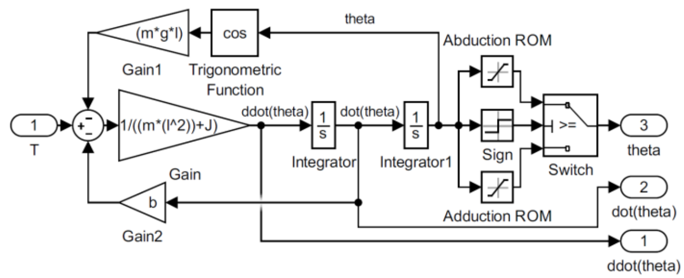

Fig. 3. Wrist abduction/adduction dynamic model in Simulink.

TABLE I
WRIST JOINT ROMS

Movement	Normal ROM [°]	Functional ROM [°]
Flexion	85	15
Extension	85	30
Abduction (radial deviation)	15	15
Adduction (ulnar deviation)	30	15

Parameters of the dynamic models are obtained from an anthropometric analysis and are listed in Table II, where the mass of the hand is function of the body mass M of the patient, the length of the hand is function of the height H of the patient, and the gravity center and radius of gyration are function of the length of the hand [13,14].

TABLE II
PARAMETERS OF THE DYNAMIC MODELS

Parameter	Symbol	Value	Units
Mass of the hand	m	0.006·M	[kg]
Length of the hand	L	0.108·H	[m]
Proximal gravity center	l	0.506·L	[m]
Radius of gyration of the hand	K	0.297·L	[m]
Moment of inertia of the hand	J	$m \cdot k^2$	[kg· m^2]
Damping coefficient	b	0.1	[N· $m \cdot s$]
Gravity	g	9.81	[N· $m \cdot s$]

For simulation, a closed-loop angular displacement PID control is built in the dynamic model (as illustrated in Fig. 4 for the flexion/extension model), representing the human neuromusculoskeletal control [15]. The input to the controller is the tracking error, defined as the difference between the desired reference trajectory and the angular displacement of the hand, and the output is the torque applied to the joint to produce the desired movement. This implementation allows the estimation of the joint torque during flexion/extension or abduction/adduction in any anthropometrical configuration (body mass and height) and any ROM, becoming a useful tool for selecting exoskeleton actuators.

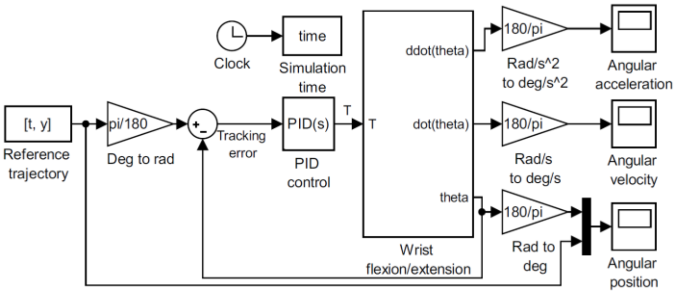

Fig. 4. PID control on the wrist flexion/extension model in Simulink.

PID control is a feedback classic technique based on the transfer function shown in (9), composed of three terms: proportional (K_p), integral (K_i), and derivative (K_d). Proportional action increases system response time, integral action reduces steady-state error, and derivate action responds to the error evolution in time [16]. The controller was tuned experimentally until achieving the best tracking performance with a PD-nature, where $K_p = 100$ and $K_d = 10$.

$$PID(s) = K_p + \frac{K_i}{s} + K_d s \tag{9}$$

The models are simulated for the average Colombian adult mass and height [17] using sinusoidal waves as reference trajectories [15] with the maximum ROMs of the wrist movements (Table I). The results are shown in Fig. 5-8, where each figure consists of two plots: (a) angular displacement tracking, where the dotted line is the reference trajectory and the solid line the hand displacement, and (b) joint torque required to execute the movement. From the graphical results is observed that the dynamic models achieve precise tracking of the reference trajectories, and the maximum torque is obtained in the fully horizontal position of the hand ($\theta = 0[°]$ relative to the x axis of Fig. 1) with a maximum value of 3.8 [kg·cm], and as the hand flexes, extends, abducts, or adducts, the torque decreases, due to a reduction of the perpendicular distance between the weight vector and the joint.

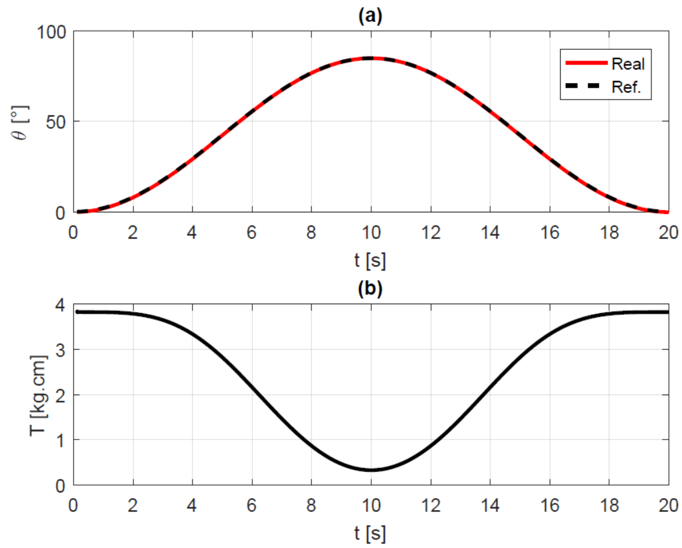

Fig. 5. Wrist extension of 85[°]: (a) angular displacement and (b) torque.

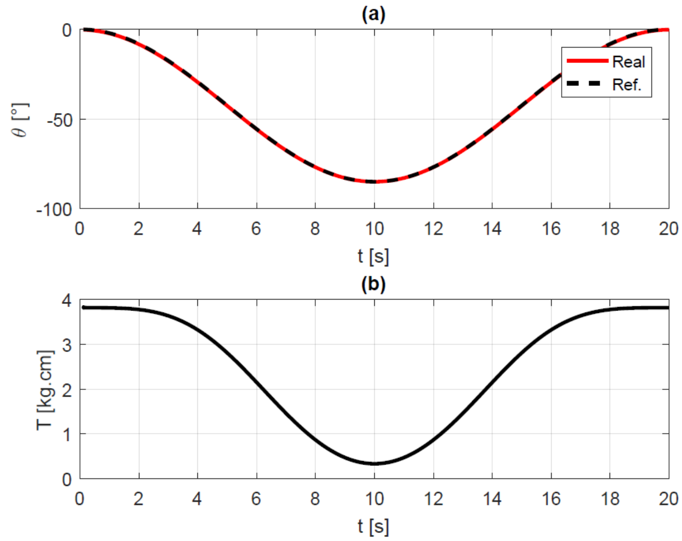

Fig. 6. Wrist flexion of 85[°]: (a) angular displacement and (b) torque.

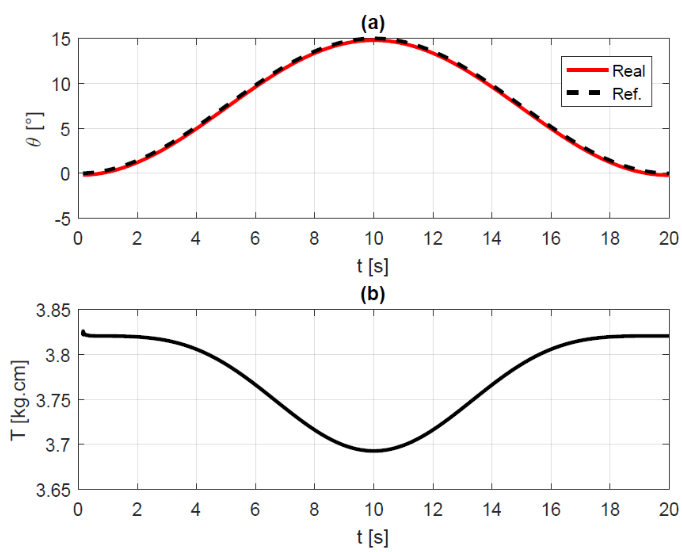

Fig. 7. Wrist abduction of 15[°]: (a) angular displacement and (b) torque.

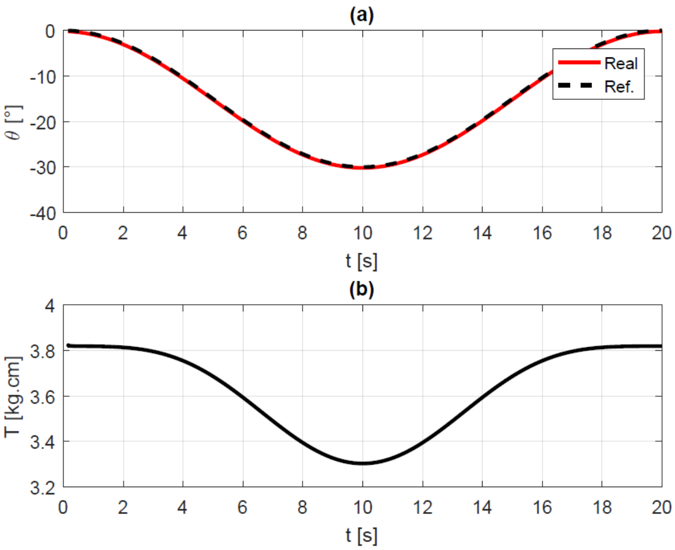

Fig. 8. Wrist adduction of 30[°]: (a) angular displacement and (b) torque.

These dynamic models constitute as a powerful tool to estimate wrist joint torques in flexion/extension and abduction/adduction for any ROM, velocity, type of reference trajectory, and anthropometric configuration of the patient (body mass and height), and therefore, could be used to select the most suitable actuators for the exoskeleton. The dynamic modelling presented here using Euler-Lagrange formulation can be extrapolated to the analysis of the fundamental movements of any joint of the human body as shown in [18,19].

III. Exoskeleton design and construction

The wrist exoskeleton is designed in SolidWorks CAD software considering its two DOF related to flexion/extension and abduction/adduction and the anthropometric data of average Colombian adults [17]. As shown in the exploded view of Fig. 9, the exoskeleton consists of eight elements: (1) principal support, to hold the exoskeleton mobile elements and the electronic circuit; (2) forearm support, to attach the exoskeleton to the patient's forearm through adjustable straps; (3) servomotor base, to hold the flexion/extension servomotor; (4) arched element, driven by the servomotor to perform flexion/extension, and used to hold the abduction/adduction servomotor; (5) bearing, inserted in the principal support to allow low friction movement of the arched element; (6) T-element, fixed to the patient's hand through a glove and adjustable straps, and coupled to the servomotor to perform abduction/adduction, (7) two servomotors, and (8) two motor couplings, to connect the motor's shaft to the mobile elements (T-element and arched element).

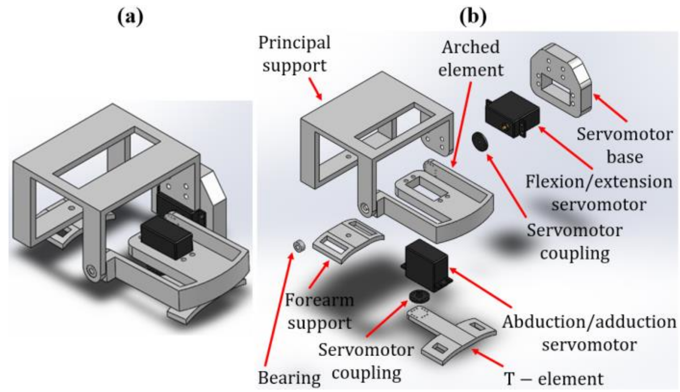

Fig. 9. Wrist rehabilitation exoskeleton in SolidWorks: (a) isometric and (b) exploded view.

The servomotors were selected considering two design requirements: (1) supply the wrist flexion/extension and abduction/adduction functional ROMs of Table I, and (2) supply the required joint torque, whose maximum value according to the simulation results of section II was approximately 3.8 [kg·cm]. A safety factor of 1.5 is introduced in the torque, since it was estimated considering average anthropometric data, resulting in a maximum value of 5.7 [kg·cm]. This allows the exoskeleton to be used by patients with greater body masses and heights than the average Colombian adult. Considering both design requirements, servomotors MG996R are selected, capable of delivering a maximum torque of 11 [kg·cm] when supplied with 6 [V] DC and with a maximum rotation of 120[°].

The exoskeleton elements were manufactured through 3D printing in 0.85 [mm] thick polylactic acid (PLA) to guarantee rigid support and lightweight and were assembled as established in the exploded view of Fig. 9. The result of the design and construction is the wrist exoskeleton shown in Fig. 10 and 11, that has a total mass of 0.64 [kg] including electronics (servomotors, microcontroller, and batteries).

Fig. 10. Isometric view of the wrist rehabilitation exoskeleton.

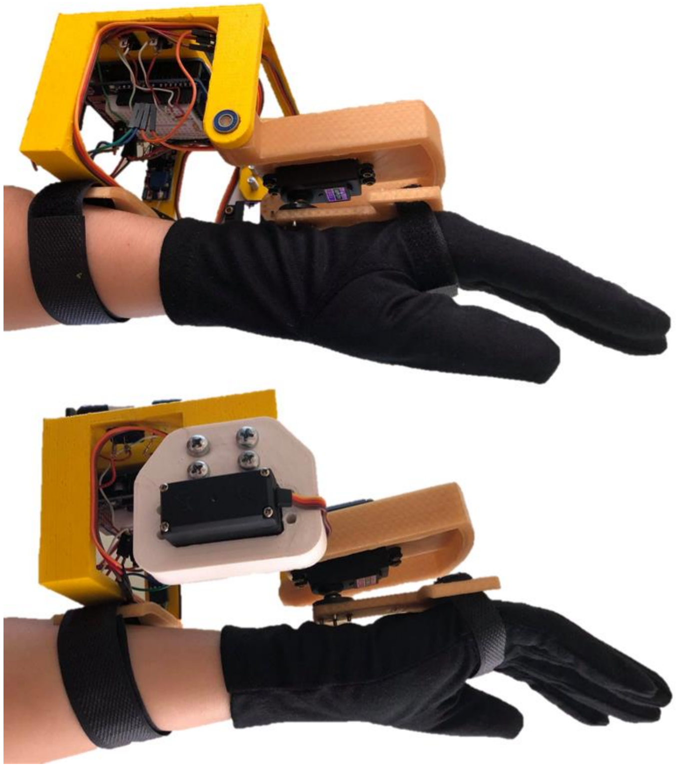

Fig. 11. Side views of the wrist rehabilitation exoskeleton.

IV. EXOSKELETON CIRCUIT AND CONTROL

The electronic circuit of the exoskeleton is illustrated in Fig. 12 and consists of an Arduino UNO microcontroller, two MG996R servomotors, an HC06 Bluetooth module, an MT3608 voltage booster module, three switches, a battery holder (x4 in series), 4 rechargeable 1.2 [V] and 2500[mAh] batteries, and a 9 [V] battery. The Arduino UNO board is used to control the movements of the servomotors according to the rehabilitation therapy parameters introduced in a mobile app, where the cellphone establishes Bluetooth communication with the Arduino through the HC06 module. Three switches, each one with a LED indicator, are installed in the exoskeleton, the first one (power switch) connected to the battery holder to connect or disconnect the exoskeleton power supply and designed as a safety feature for the patient, the second one (movement switch) connected to a digital pin of the Arduino to select the desired type of movement (flexion/extension or abduction/adduction), and the third one (start switch) connected to another digital pin to start or stop the execution of the rehabilitation therapy. The Arduino is powered by the 9 [V] battery and the MG996R servomotors by the rechargeable batteries through the MT3608 voltage booster module, which elevates the voltage from 4.8 to 6 [V] to obtain the desired output torque. This configuration allows independent voltage supply for the control and power stages of the exoskeleton, to guarantee the current for the servomotors.

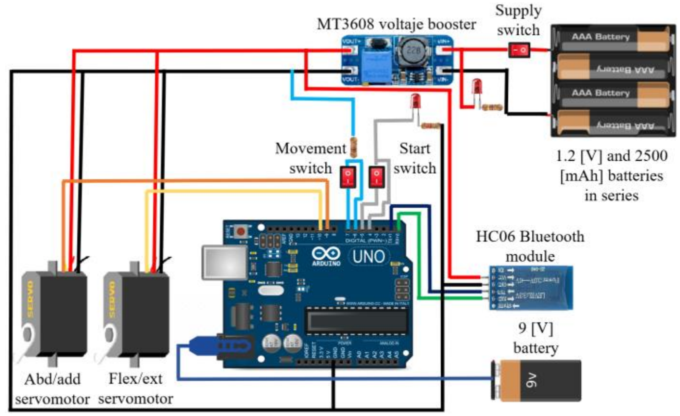

Fig. 12. Exoskeleton electronic circuit.

The control system is programmed in Arduino as depicted in the flowchart of Fig. 13. The code starts with the Bluetooth connection between the cellphone and the HC06 module, and once the connection is established the patient or therapist can introduce the therapy parameters (ROM, number of repetitions, and speed) in the mobile app. The Arduino reads the parameters and establishes accordingly the rotation and speed commands for the servomotors. Then, the patient or therapist selects the desired type of movement (flexion/extension or abduction/adduction) through the movement switch, and with the start switch allows the beginning of the rehabilitation therapy. If the start switch is off, the exoskeleton remains in the fully horizontal hand position, and if the start switch is on, then the control drives the servomotors by using the <Servo.h> library. Once the therapy is over, the patient can select another therapy parameters and run again the control algorithm. The start switch works as a physical emergency button since it enables or disables the motion of the motors inside the control algorithm, becoming a safety feature of the exoskeleton whenever the patient feels pain or discomfort. The control system is considered open-loop since no feedback from the actual hand position is generated. However, the servomotors are driven taking advantage of the internal closed-loop control programmed through the <Servo.h> library.

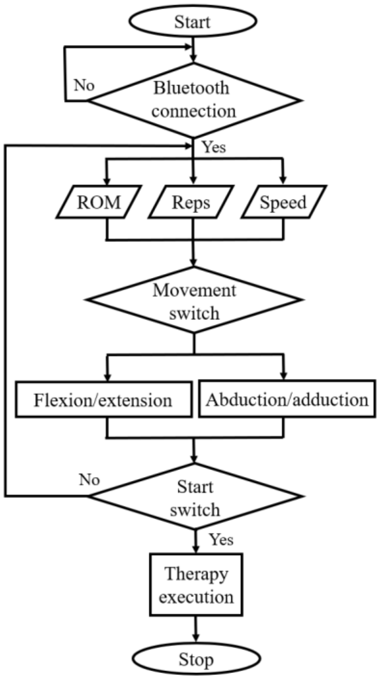

Fig. 13. Flowchart of the exoskeleton control.

The mobile app to enter the rehabilitation therapy parameters is developed for Android platform using MIT App Inventor. Three parameters are established in the app: (1) movement ROM, (2) number of repetitions, and (3) speed. As shown in Fig. 14, the app consists, from top to bottom, of one button to connect or disconnect the Bluetooth communication, six buttons to select the movement ROM from 5 to 30[°] as established in the functional ROMs of Table I, ten buttons to select the number of repetitions, and three buttons to select the speed of the therapy. Inside the app there is an additional safety feature, since if the disconnect button is pressed, then the control algorithm will stop the motion of the motors.

Fig. 14. Mobile app to enter rehabilitation therapy parameters.

V. Exoskeleton functional tests

Functional tests of the wrist exoskeleton were carried out to verify the angular displacement tracking performance. The results were quantitatively evaluated in terms of the relative maximum error (RME) defined by (10), where θ_d is the desired angular displacement (reference trajectory) and θ_m the measured angular position of the hand [20,21].

$$\% RME = \frac{\max |\theta_d - \theta_m|}{\max |\theta_d|} \tag{10}$$

Tests were conducted on a patient whose anthropometric characteristics are within the average Colombian adult, maintaining speed and number of repetitions constant throughout the different evaluated ROMs. The results are summarized in Table III, where the largest errors are obtained for small angular displacements, but in general, they are kept under 10% for all the evaluated ROMs.

TABLE III
Exoskeleton functional tests results

Movement	θ_d [°]	θ_m [°]	% RME
Flexion	5	5.2	4
	20	20.1	0.5
	30	27.5	8.333
Extension	5	4.7	6
	20	19.8	1
	30	31	3.333
Abduction	5	4.5	10
	10	10.5	5
	15	14.5	3.333
Adduction	5	4.7	6
	10	9.8	2
	15	14.6	2.667

VI. Conclusions

This work presented the modelling, design, construction and control of a wrist flexion/extension and abduction/adduction rehabilitation exoskeleton. The dynamic models of the wrist movements were obtained using Euler-Lagrange formulation and were built in Simulink of MATLAB using the differential equations derived from the analysis. A PID feedback control, representing the human natural neuromusculoskeletal control, was built in the dynamic models for simulation of rehabilitation therapies using different ROMs and under different anthropometric data (patients with different body masses and heights). This allows the model to become a useful tool for the actuator selection, since it estimates the wrist joint torque required to produce flexion/extension or abduction/adduction. Simulations were carried out considering the average Colombian adult, and using the maximum ROMs as input, to obtain a maximum wrist joint torque of 3.8 [kg·cm] in the fully horizontal position of the hand.

The exoskeleton was designed in SolidWorks CAD software, composed of eight elements (principal support, forearm support, servomotor base, arched element, bearing, T-element, two servomotors, and two motor couplings) and manufactured through 3D printing in PLA. MG996R servomotors were selected since they can deliver a maximum torque of 11 [kg·cm] when supplied with 6 [V] DC and maximum rotation of 120[°].

The control system of the exoskeleton was coded in an Arduino UNO microcontroller using the <Servo.h> library to run the servomotors. The rehabilitation therapy parameters (wrist ROM, number of repetitions, and speed) were entered by the patient or therapist through a mobile app developed in MIT App Inventor, which established Bluetooth connection with the Arduino by means of an HC06 Bluetooth module. The result of the design, construction and control is a wrist lightweight exoskeleton (total mass of 0.64 [kg] including servomotors, microcontroller, and batteries) with the ability to be used in rehabilitation of flexion/extension and abduction/adduction in telemedicine-based therapies.

Functional performance tests of the exoskeleton were performed considering different flexion/extension and abduction/adduction ROMs. The results were quantitively evaluated using the relative maximum error (RME), where the exoskeleton showed angular displacement tracking with errors under 10%.

In future works it is intended to develop closed-loop control strategies to minimize the RME of the angular displacement and guarantee a more precise tracking of the reference rehabilitation trajectories. To implement closed-loop control techniques it is necessary to provide the exoskeleton with two sensors (e.g., linear potentiometers) to measure angular displacements during flexion/extension and abduction/adduction. The inclusion of sensors would expand the capabilities of the exoskeleton, not only by means of tracking performance, but also because it would allow the measurement of ROM evolution in rehabilitation therapies. In this sense, the wrist rehabilitation exoskeleton could be used for active and passive rehabilitation practices. Additionally, future work includes the execution of functional test with different anthropometrics configurations of patients (body mass and height), ROMs, velocities, and number of repetitions. These tests will be carried out with the accompaniment of health rehabilitation professionals to achieve a broad evaluation of the performance of the exoskeleton.

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