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Design, Development, and Control of a Tendon-actuated Exoskeleton for Wrist Rehabilitation and Training

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***Abstract*— Robot rehabilitation is an emerging and promising topic that incorporates robotics with neuroscience and rehabilitation to define new methods for supporting patients with neurological diseases. As a consequence, the rehabilitation process could increase the efficacy exploiting the potentialities of robot-mediated therapies. Nevertheless, nowadays clinical effectiveness is not enough to widely introduce robotic technologies in such social contexts. In this paper we propose a step further, presenting an innovative exoskeleton for wrist flexion/extension and adduction/abduction motion training. It is designed to be wearable and easy to control and manage. It can be used by the patient in collaboration with the therapist or autonomously. The paper introduces the main steps of device design and development and presents some tests conducted with an user with limited wrist mobility.**

I. Introduction

For a person with disabilities, technology plays an important role, since it offers the opportunity to radically change her/his everyday life. Tools and supports can help in the autonomy of activities of daily living (ADLs), communication, study, and in the process of integration. Nowadays there are countless technologies in the medical and assistive field which allow people with disabilities to have a life that is almost completely "normal".

Thanks to the progresses in health-care and medicine, the vast majority of humans are living a longer and healthier life than in the past. On the other hand, the aging factor is significant in rehabilitation, since most of the chronic diseases related to the musculoskeletal and nervous system are within the aged people. According to the World Health Organisation (WHO) statistics, nearly one billion people worldwide are suffering due to the neurological and musculoskeletal diseases [1].

Technology in general and more specifically assistive robots will be effective if devices are accepted and regularly used by the people with physical disabilities in their everyday life, outside hospitals, laboratories and rehabilitation centers. In this perspective, it's worth to mention the Cybathlon initiative, an international competition in which people with physical disabilities compete in completing everyday tasks using latest robotic technology [2].

Rehabilitation has the objective of maintaining or recovering the patient's physical abilities. Taking advantage of all the functional systems that are intact, it seeks to guarantee better control of one's own person and the surrounding environment, reducing the perception of discomfort deriving from the limitations imposed by the disease. Its goal is to encourage, at least partially, the recovery of lost functionality and to enable the patient to be more autonomous in ADLs.

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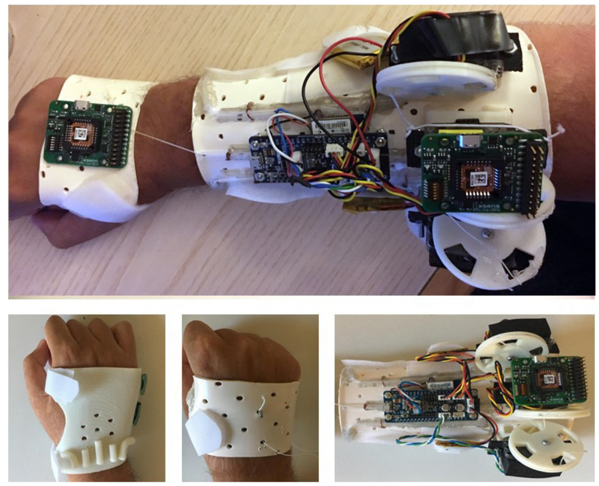

Fig. 1: Exoskeleton prototype. Top figure: the exoskeleton worn by the user. Bottom figures: two versions of the hand support and forearm support.

Traditional physical therapies improve functional recovery, but usually they are expensive, require a lot of workforce, and the patient and the therapist must physically meet for the whole therapy duration.

For this reason the use of robotic devices can be beneficial, as it requires a smaller workforce, and allows a more lasting and more intense therapy. An evident advantage of these technologies is the possibility of realizing the rehabilitation process in patient's home, providing the possibility of more frequent and accessible exercises [3].

One of the first examples of robot rehabilitation has been presented in [4], this study concluded that patients in the post-stroke sub-acute phase exhibit greater functional recovery if they received robotic assistance in addition to traditional therapy. Robots in rehabilitation replace the physical effort of the therapist, facilitating recovery and maintenance of patient physical abilities, with advantages in terms of availability and the therapist's strength. The use of robots in rehabilitation needs to be used according to well defined neuroscientific principles [5].

In general, the upper limb plays an important role for all daily activities, and various exoskeleton devices have been developed as support tools for this part of the body [6],

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[7]. In particular, different devices specifically developed for the wrist have been presented [8]–[11]. Notwithstanding the technological developments and the evidence of clinical effectiveness of robotic technologies for upper-limb neuro-rehabilitation, there are still some limits in their diffusion. In [12] the main technological, behavior, and economic barriers, and communication biases between the producers of the technologies that still need to be solved are discussed.

In this work, we present an exoskeleton for wrist actuation that can be used both for daily activities as well as for long term rehabilitation process (Fig. 1). The main criterion pursued in the design process is the ease of use. The patient, even with limitation in upper limb motion capabilities, can wear the device and use it also without the need of external support. The exoskeleton structure is made of thermoplastic material, that can be adapted to user's specific needs. The wrist is tendon-actuated and the number of components has been limited as much as possible. Actuators, electronic components, and batteries are included in the forearm part of the exoskeleton, the data transmission from/to the PC is managed by a wireless system. A graphical user interface allows the user to choose the exercise and to set its parameters, as well as to monitor it during the execution.

Since the exoskeleton hand and arm parts are not constrained by the mechanical structure, a key aspect of the proposed exoskeleton is represented by the tracking of wrist movements. Also for this aspect, we selected a tradeoff between accuracy of the estimation and and ease-of use of the device. The solution that we developed for the tracking system is based on two Inertial Measurement Units (IMUs), which are low-cost electronic devices integrating an accelerometer and a gyroscope on a single board. In this work, we developed data acquisition and processing of IMU sensors, their translation in biomechanical information and online data monitoring. The resulting tracking system is able to record the user's motion (*e.g.*, an exercise suggested and guided by the physiotherapist), to monitor/control exercises guided by the exoskeleton, and to monitor patient's range of motion and improvements. To the best to our knowledge, this represent the first attempt to combine all the aforementioned features in a single wearable device.

II. Tracking with IMUs, state of the Art

Several techniques for human body tracking are available, both in a research phase and off-the-shelf. Optical trackers, camera based system, and fabric integrated sensors are the most common and widespread technologies.

Optical tracking systems such as Optitrack (NaturalPoint Inc., USA) and Vicon (Vicon Motion Systems, UK) exploit markers to estimate in real time the human posture with high precision and accuracy. On the other hand, they need a structured environment to work properly, thus they are neither wearable/portable, nor usable in outdoor scenarios. Towards the concept of portability, camera-based tracking algorithms became a common solution due to improvements in computer vision techniques and progressive growth in GPU computational capabilities.

In [13], the authors developed a tracker which employed a commercial RGB camera to reconstruct the human kinematic chain. Focusing on the upper body, commercially available devices, like the Leap Motion (Leap Motion Inc., USA), allow to simultaneously estimate the full hand and wrist configurations. However, camera-based solutions have some known limitations: cameras might not work correctly in an outdoor environment due to the lighting interference and occlusions of the body itself may induce a poor estimation.

Another way to estimate the pose of the human body is to use Micro Electro-Mechanical Systems (MEMS) technology. In particular, a MARG (Magnetic, Angular Rate, and Gravity) board consists of a MEMS triaxial gyroscope, accelerometer, and magnetometer. The sensors board can be integrated with a wearable device and used to reconstruct the pose of the human body. The main drawback of MARG sensors is that the majority of the algorithms rely on the magnetometer to estimate the orientation, thus they are sensitive to local variations in the magnetic field. In spite of that, tracking systems based on this technology are commercially available and allow to accurately track the whole body, both outdoor and indoor, in unstructured environments, under different lighting conditions, and free from grounded/bulky hardware [14]. Focusing on arms and hands, systems using inertial sensors were proposed in [15], [16]. In [15], the authors made a whole-hand tracking system by means of sensors placed on the phalanges A similar device, using triaxial accelerometers, was developed by Kim *et al.* [17]. A sensing glove composed of inertial and magnetic sensors was proposed in [18]. For each finger, the authors exploited only triaxial gyroscopes and accelerometers.

By considering the above mentioned tracking methodologies, we focus on inertial MEMS technology to estimate the hand pose. This choice meets the requirements of designing a wearable, robust, and low cost sensing system capable of working indoor and outdoor, with no limitation in lighting condition. Moreover, differently from MARG devices the magnetometer is not used to compute the orientation, thus the orientation estimate is reliable also in presence of magnetic disturbances (*i.e.*, the irregular magnetic field generated by the motors).

III. Device description

A. Mechanical design, kinematic requirements

The the exoskeleton is composed of two independent rigid parts, one worn on the hand and one fixed on the forearm. Parts are connected by means of three tendons that are fixed on one side to the hand. On the other side, they are wrapped around the pulleys connected to the shafts of three motors, whose bodies are fixed on forearm support. Assuming that the wrist can be modeled as a 2-DoF joint, three is the minimum number of tendons that is necessary to actuate them (see for instance, the results presented in [19]).

Let us indicate with θ_a and θ_e the adduction/abduction and flexion/extension rotations, respectively. Due to the above introduced motion requirements, the following variation ranges are considered:

$$-45^\circ < \theta_a < 20^\circ, \quad -65^\circ < \theta_e < 65^\circ$$

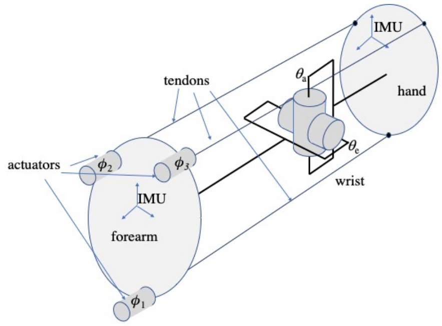

Fig. 2: Wrist and exoskeleton scheme. The wrist is modelled as a 2 DoFs universal joint, enabling the flexion/extension θ_e and adduction/abduction θ_a of the hand w.r.t. the forearm. Three tendons connect the exoskeleton hand and forearm supports and are actuated with three motors. Their angular rotation is indicated with ϕ_i.

We indicate with $\phi = [\phi_1,\ \phi_2,\ \phi_3]^T$ a vector collecting motor rotation angles and with $\theta = [\theta_a,\ \theta_e]^T$ a vector collecting wrist rotation angles. The wrist/exoskeleton system can be modeled as a 2-DoF parallel mechanism with three actuators, as sketched in Fig. 2. An inverse kinematics relationship can be defined from the analysis of the system. This relationship can be considered linear with good approximation

$$\boldsymbol{\phi} = J_i \theta \tag{1}$$

Inverse kinematics Jacobian matrix J_i is 3×2 and its terms depend on wrist and exoskeleton parameters. It is interesting to notice that ϕ values cannot be randomly selected, but need to belong to the 2-dimensional subspace $\mathcal{Q}$ whose basis is defined by J_i columns. If $\tilde{\phi} \in \mathcal{Q}$, we can solve the direct kinematic problem

$$\theta = J_i^{\#} \tilde{\boldsymbol{\phi}}, \tag{2}$$

where $^{\#}$ indicates the pseudo-inverse.

Indicating with $\tau_w = [\tau_a, \tau_e]^{\mathrm{T}}$ the adduction/abduction and flexion/extension wrist torques applied by the exoskeleton and with $\tau_m = [\tau_1, \tau_2, \tau_3]^{\mathrm{T}}$ the torques applied the motors, the following static relationship can be set:

$$\tau_w = J_i^T \tau_m \tag{3}$$

B. Mechanical design

Supports: In the first phase of mechanical design we compared and evaluated different solutions and manufacturing processes. Realizing the entire exoskeleton (the part of the hand and the part of the forearm) by means of additive manufacturing processes was not the optimal solution, especially for the part of the forearm, since a relatively complex process was necessary to adapt the structure to user's forearm specific features, including for instance a 3D scan of the upper limb, the adaptation of 3D CAD files of the support to the specific forearm, and the manufacturing process itself. For the forearm support, we decided to adapt a solution available for orthoses consisting in shaping a plate of thermoplastic material directly on user's forearm [20]. Regarding the support on the hand, this component has more limited dimension, more complex geometry and relatively higher mechanical solicitations w.r.t. forearm support, so the advantage of thermoplastic material was not evident. For these reasons different versions were designed, some of them were realized with Acrylonitrile Butadiene Styrene (ABS) material processed by a 3D printer, starting from a 3D-CAD model of the hand and exploiting different shapes and assemblies, to verify which was the optimal one in terms of wearability. A 3D CAD model of the supports is reported in Fig. 3.

Fig. 3: CAD model of exoskeleton supports on the hand and on the forearm.

Actuators, sensors, electronic components: Three Dynamixel XL-320 motors were employed. Each motor can generate a stall torque up to 0.39 Nm @ 7.4V, a value that is suitable for the exoskeleton applications. The position of the motors and the routing of the tendons on the forearm was chosen so to guarantee both a sufficient comfort level to the user and a good transmission efficiency. The exoskeleton range of motion depends on the rotation q_i ($0 \leq q_i \leq 360°$) of each motor, resulting in a more effective control strategy.

A 32bit Arm Cortex-M3 microcontroller controls the motors by means of a library provided by the suppliers of the OpenCM9.04 board. While a RN42 Bluetooth module embedded in the board, communicates data with a PC application that allows the user to select and monitor the exercise.

Overall, the forearm support includes the following components: a board OpenCM9.04 C-Type; a Bluetooth module RN42; three Dynamixel XL-320 Motors; two batteries of 3.7 V, 500 mA; one IMU sensor (Xsens MTi-3). The hand support includes only one IMU sensor. The IMU placed in the hand is powered using the batteries placed in the forearm. IMUs raw data are transmitted to a remote PC using Xbee modules.

Overall features: An image of the exoskeleton prototype, worn by the user, is reported in Fig. 1, whereas its main features are summarized in Table I. It can be noticed that the overall weight is quite low, about 300 g, and also the overall encumbrance is quite small, compared to other devices for the same purpose [21], [22].

IV. Device control

A. IMU

As aforementioned in the introduction, a viable way to estimate the orientation of the hand is to use IMU sensors.

Parameter	Value	Unit
Range, flexion/extension	± 65	deg
Range, adduction	45	deg
Range, abduction	20	deg
Weight	300	g
Actuator stall torque	0.39	Nm
Actuator dimensions	$24 \times 36 \times 27$	mm
Actuator weight	16.7	g
Actuator no load speed	114	rpm
Max yield stress, forearm support	26	MPa
Max yield stress, hand support	34	MPa
Max tendon force	15	N

TABLE I: Main features of the wrist exoskeleton.

The orientation of the hand with respect to the forearm (*i.e.*, the wrist angles) is computed by means of two boards. An IMU is placed on the back of the hand, whereas a second one is firmly attached to the exoskeleton. To compute the orientation of each board, we exploited and adapted the algorithm presented in [23]. The algorithm computes, for each IMU, the actual orientation with respect to its initial pose. Raw data from the sensors are collected and sent wirelessly to an external PC in charge of all the mathematical computations. The update rate for the system is 1kHz. In what follows, we describe the procedure to calibrate the sensing glove and briefly outline the hand tracking algorithm based on IMU sensors.

1) Calibration: Each IMU board requires an initial calibration, which consists of two steps. In the first step, the user is asked to displace the hand in a known a-priori position, *e.g.,* the user places the hand in a flat surface. In this phase, each IMU board collects 200 samples to estimate the gyroscope bias. In the second step, we compute the offset quaternion between the hand and the forearm.

2) Hand tracking algorithm: In what follows, we summarize the joint angles estimation, for more details, the interested reader is referred to [23]. In this work, we use quaternions to estimate the orientation of a single IMU sensor with respect to a reference frame. Using quaternion allows us to overcome the problems introduced by the Euler angles, for instance, the gimbal-lock problem and the issues related to the trigonometric functions. In this algorithm and in the entire paper, we use the following convention to represent a quaternion: $q = [w\ x\ y\ z]$, where w is the real number.

Let ${}^{S}q_H(t)$ and ${}^{S}q_F(t)$ be the quaternions that express the orientation, with respect to the Sensor reference frame Σ_S, of the frames associated to the hand, and to the forearm, respectively. Let ${}^{F}\hat{q}_H$ be the offset quaternions between the hand and the forearm, estimated during the aforementioned calibration phase. At a certain time instant t, the orientation of the hand referred to the forearm can be computed as

$$ {}^{F}q_H(t) = {}^{F}q_S(t) \otimes {}^{S}q_H(t), $$

where ${}^{F}q_S(t)$ is the conjugate quaternion of ${}^{S}q_F(t)$. Then, the quaternion that describes the orientation of the hand with respect to the initial configuration results

$$ q_H(t) = {}^{F}q_H(t) \otimes {}^{H}\hat{q}_F $$

As a final step, the result is converted into *Euler Angles*.

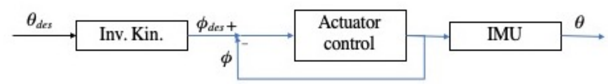

Fig. 4: Exoskeleton control scheme.

B. Control

Exoskeleton control scheme is sketched in Fig. 4. The input for the control scheme is the desired trajectory $\theta_{des} = [\theta_{a,des}, \theta_{e,des}]$, that can be assigned by the user through the graphical user interface or previously recorded by IMU sensors. θ_{des} values can be recorded for example during the execution of an exercise in which the exoskeleton is not actuated and wrist motion is manually guided by the physiotherapist. Through inverse kinematic analysis, wrist desired rotation angles are θ_{des} transformed in references for the actuators' control systems ϕ_{des} (eq. (2)). Actual wrist movement θ is monitored by the tracking system based on IMU sensors during the exercise execution.

C. User interface

A Matlab GUI interface (Fig. 5) has been developed to set exercise parameters and monitor them. When opening the application, the device has to be connected to the PC through the Bluetooth module.

Once the exoskeleton is connected, the user can set a home position, or start the exercise. The user can also choose between an automatic or manual device control. Some exercises are already available in the interface, they are the typical wrist exercises, like flexion/extension and abduction/adduction motions. For each exercise, the user can select three different speeds (low, medium and high) and a running time, thanks to the relative drop-down menus. The user can also manually set a specific speed value and a specific time duration for the exercise.

Once the *start* button is activated, the interface software takes all the data set by the user and send it to the exoskeleton via Bluetooth communication. When the exercise starts, the software reads the values of motors' rotation angles and torques and plots them on a diagram visible on the interface.

The manual control of the device is realized by four buttons on the interface: flexion (*DOWN*), extension (*UP*), ulnar adduction (*LEFT*) and radial abduction (*RIGHT*). While one of the buttons is activated, the corresponding motion is executed, until fixed maximum thresholds are reached. Finally the *disconnect* button implements a function that closes the Bluetooth communication and exits the program.

V. Tests

Test 1: The system was evaluated on a subject with a severe limitations in extension motion (movement in flexion are with reduced problems) and some limitations in radial

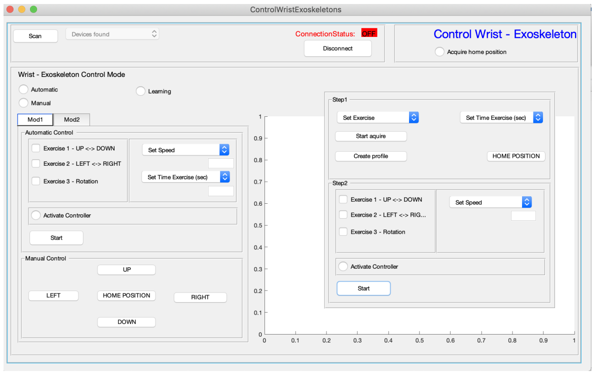

Fig. 5: Graphical user interface realised for device control.

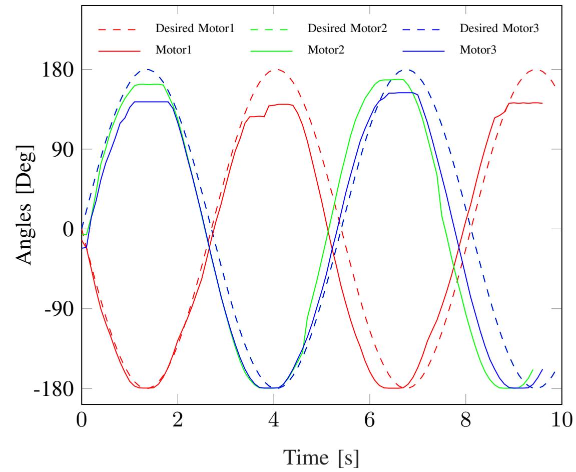

Fig. 6: Test 1, Flexion/Extension representative trial. Dashed curves show the desired angular position of the motors, solid ones represent the actual values. Desired motion of motors 2 and 3 are overlapped.

adduction and ulnar abduction. Two typologies of exercises suggested by the physiotherapist were exploited as validation mean. A first set of tests were carried out to evaluate how motors follow a specific desired motion. Flexion/extension motion is obtained by setting the same profile to actuators 2 and 3, and the opposite to actuator 1. To simulate a flexion/extension movement, the following reference values were set to the actuators

$$\phi_{2,des} = \phi_{3,des} = \alpha \sin(\omega t), \;\; \phi_{1,des} = -\alpha \sin(\omega t)$$

with $\alpha = 1$ rad, $\omega = 1.1624$ rad/s and $0 < t < 10$ s. Each trial lasted 10s. References and measured values of rotation angles of a representative trial are reported in Fig. 6. The figure shows how the actuators are able to follow the profile for the entire duration of the exercise. Ten repetitions of the trial were performed and for each reference actual value of the motors were recorded. We observed that the average error in following the reference is $9.06°$. Then we simulated the ulnar adduction and radial abduction. To reproduce this motion, motor 1 is maintained steady, whereas motors 2 and 3 pull their tendons with opposite movements. To recreate this behavior the following reference profiles were used to control the motors:

$$\phi_{1,des} = 0, \;\; \phi_{2,des} = \alpha \sin(\omega t), \;\; \phi_{3,des} = -\alpha \sin(\omega t)$$

with $\alpha = 1$ rad, $\omega = 1.1624$ rad/s and $0 < t < 10$ s. Ten consecutive trials were performed. For each repetition desired rotation angle and real value of the motors were recorded. We observed that the average error in tracking the angular profile was $9.94°$.

Test 2: Another set of tests were aimed at verifying the capability of recording an exercise performed by a physiotherapist and reproduce it with the exoskeleton. As graphically reported in Fig. 5, the system is able to record hand motion with respect to the forearm through the tracking system. The recorded movement can be therefore transformed in reference values for the actuators and reproduced by the exoskeleton. A physiotherapist and a patient with limited mobility were involved in this test. We asked to the physiotherapist to gently move for twelve seconds the hand of the patient while the system was recording the hand orientation with respect to the forearm. Ten adduction/abduction and ten flexion/extension exercises were carried out. One representative trial for this type of tests are reported in Fig. 7. For the sake of space, we report in the paper only the motor reference/actual values for the first experiment and the estimated orientation data for the second one. Interested reader is referred to the attached video for further details and plots.

VI. Discussion

The increasing need for rehabilitation and assistance for people with disabilities, implies that robotic care and rehabilitation may play an important role in the years ahead. Nowadays, research on the use of robotic systems in different fields related to health-care is widespread and interesting solutions are available in the literature. Robots are currently viewed as advanced therapy tools, even if in most of the application therapist's guidance is necessary. The availability of more autonomous and intelligent processes in neurorehabilitation could increase the effectiveness of rehabilitation process, since it would allow to increase the frequency of the exercises, reduce the costs for the patient and for the overall health-care system. However, there are still some barriers in the diffusion of robotic systems in the daily life of the people, due to their complexity and costs.

In this paper, we focus on the rehabilitation of upper limb and we present the design and prototype of a tendon actuated exoskeleton for wrist rehabilitation. The device is composed of two supports, one worn on the hand and one fixed on the forearm, connected by three tendons actuated by three motors. The device actuates flexion/extension and adduction/abduction wrist motions. Since the device is tendon actuated, its configuration is not constrained by the mechanical structure and a tracking system is needed to estimate the relative motion between the hand and the forearm. We used two IMU sensors to perform this estimation. In the paper we describe the main components of the developed exoskeleton, its control and how it can be used to realize wrist exercises.

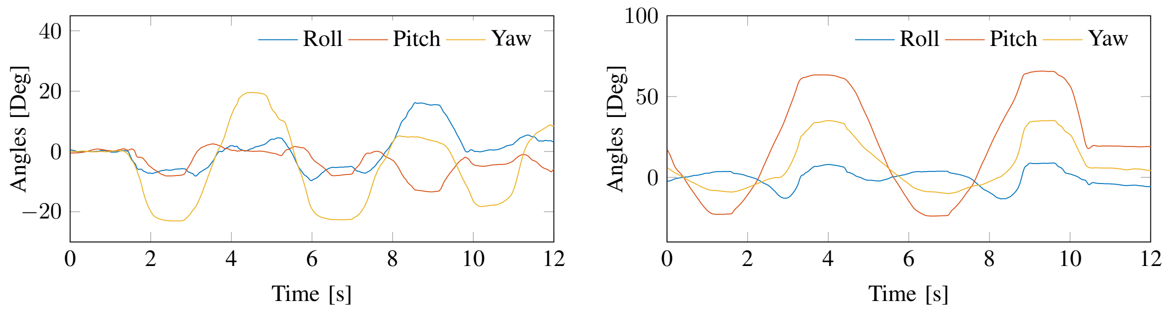

Fig. 7: Test 2 representative trials. (*left*) Adduction/Abduction motion (*right*) Flexion/Extension motion.

The main features of the developed device are:

– *light weight*: the overall weight, including actuators, sensors, batteries and electronic components, is ∼300 g;

– *wearability and adaptability*: the forearm support is made of thermoplastic material, and its shape can be adapted to user's specific characteristics, also hand support has been designed to be resistant, comfortable and easily wearable;

– *ease of use*: a graphical user interface allows the user or the trainer to easily set and monitor exercise parameters;

– *costs*: the overall cost of the components that were necessary to realize the prototype is about 150 euros, although this estimation is approximated, and that a further optimization process is needed, we believe that the price for the user will be relatively accessible for potential users.

Future developments of this research activity will include the integration of the exoskeleton with other types of sensors (*e.g.* electromyography sensors, EMG) and haptic devices, to increase its versatility in neuro-rehabilitation processes. Furthermore, we will extend the study to other upper limb movements, including elbow and shoulder and we will extend the tests to more users.

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