Pre-clinical validation of the UHP multifunctional upper-limb rehabilitation robot based platform

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***Abstract*— Interest in robotic devices for rehabilitation has increased in the last years, due to the increasing number of patients that require rehabilitation therapies, and the need to optimize existing resources. The UHP rehabilitation robot is a multifunctional device that allows to execute robotized therapies for the upper-limb using a simple pantograph based reconfigurable structure and the implementation of advanced position/force control approaches. However, in applications such as rehabilitation, where the robotic device interacts directly with the user, complying with the demands of the users is as important as complying with the functional requirements. Otherwise, the patient will reject the robotic device. Therefore, in this work the pre-clinical validation of the UHP upper-limb rehabilitation robotic platform is presented. 25 subjects of different physical characteristics have participated in the evaluation of the device, evaluating not only the correct behaviour of the device, but also its safety and adaptativity. Results show the correct behaviour of the platform, and a good acceptance rate of the device.**

I. INTRODUCTION

The loss of mobility of upper and lower limbs is one of the most frequent stroke sequels. 80% of stroke patients suffer some deficit in their motor system [1]. Nowadays, more than 26 million people around the world have to live with motor deficit due to stroke [2].

In order to recover lost mobility and improve the quality of life of stroke patients, it is necessary to carry out appropriate rehabilitation therapies. However, in most conventional rehabilitation programs, therapy hours are limited due to financial constraints [3]. In fact, in industrialized countries, stroke reaches $3-4\%$ of total health expenditure, with 76% of costs distributed in the first year after the attack, mainly concentrated in hospital and rehabilitation costs [4].

In this situation, robotic devices have been proposed to improve conventional rehabilitation therapies [5], [6]. Rehabilitation robots emulate the movements performed by a therapist, obtaining treatments of higher frequency and repetitiveness that allow to improve exercise performance and minimize recovery time. In addition, the sensors of the robotic devices allow a better analysis of the recovery status of the patient with reduced mobility. Finally, rehabilitation robots increase the motivation of the patients by the use of virtual reality software [7], [8].

Due to these benefits, over last couple of decades, many robotic devices have been proposed for rehabilitation [9], [10]. For instance, more than 100 robotic prototypes have been developed only for the rehabilitation of the upper limb [11], [12]. However, only a few, such as ARMin [13], MIT-Manus [6] or MIME [14] have been widely implemented in the clinical field.

This clinical failure is due to the fact that many rehabilitation devices are not properly adapted to the requirements of patients and therapists. In rehabilitation applications it is not enough to comply with functional therapy requirements, as the robot must also be patient-friendly, easy to use and comply with safety conditions [15]. Otherwise, the patient and therapist will reject the robotic device. Note that these requirements are different from those of conventional industrial applications, implying many differences in the design and control of the robotic device [16].

Thus, before using any robotic devices in the clinical field with reduced mobility patients, it is necessary to perform a pre-clinical validation with healthy users [17]. This validation allows to analyze the safety and robustness of the robotic device with a group of persons of different characteristics, and verify that it complies with the needs of users.

In this work, the UHP (Universal Haptic Pantograph) upper-limb rehabilitation robot platform is validated. The UHP is a reconfigurable robot that allows to easily perform rehabilitation tasks for the upper-limb, and it integrates a self-designed advanced low level force/position control algorithm that allow to perform a wide range of active/passive rehabilitation tasks[18], [19]. In order to perform the validation, a set of tests have been designed and executed with a group of 25 healthy people. To improve the communication between the UHP rehabilitation robot platform and the users, a new rehabilitation software has been implemented. In addition, to simulate patients with reduced mobility, the tests have been also performed with motion limiters that reduce the range of motion of the users.

The rest of the article is structured as follows. In Section II, the rehabilitation platform based on UHP multifunctional robot is described. In section III the design of the tests is detailed. Section IV analyzes the behavior of the rehabilitation platform when interacting with users of different

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characteristics. Finally, the most important ideas and future works are summarized in the conclusions.

II. UHP ROBOT BASED REHABILITATION PLATFORM

A. UHP multifunctional robot

The Universal Haptic Pantograph (UHP), is a multifunctional and reconfigurable rehabilitation robot designed for the training of the upper limb of patients with reduced mobility [18]. Its reconfigurable structure provides different operation modes, being ARM mode one of the most interesting ones. In this mode [19], the UHP rehabilitation robot performs semi-planar motions (Forward, Backward, Leftward and Rightward directions), as shown in Fig. 1. These motions allow training arm extension/flexion movements, and the motion of the shoulder and the elbow of the patient.

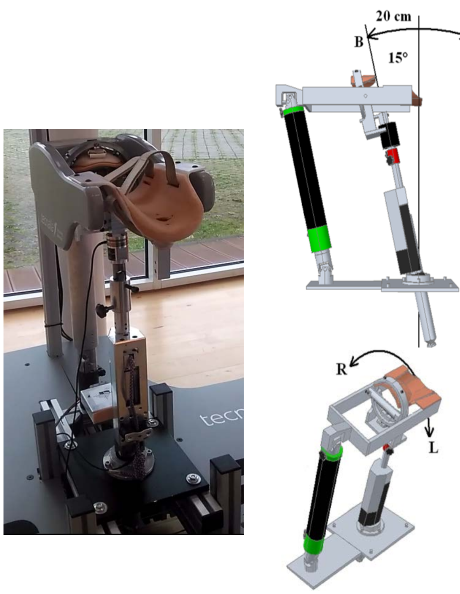

Fig. 1. UHP rehabilitation robot in ARM operating mode.

B. Rehabilitation Software

The UHP robot based rehabilitation platform uses a specific game-based rehabilitation software to improve the communication with both user and the therapist. This way, the therapist can adapt the training exercise parameters to the needs of the patient. The exercise is based on a reaching game, whose scenario uses the working area of the robot, and divides it into 5 regions (Fig 2).

The aim of the game is to patient is to move a pointer, aided by the UHP rehabilitation robot, from the initial point ($\mathbf{P_{Ini}}$) to the end of the desired region (highlighted in red in Fig 2) and then return to the initial position. The pointer is used to highlight the actual position of the robot/patient contact point ($\mathbf{P_{Cn}}$). This way, a visual feedback is provided for the actual and desired positions.

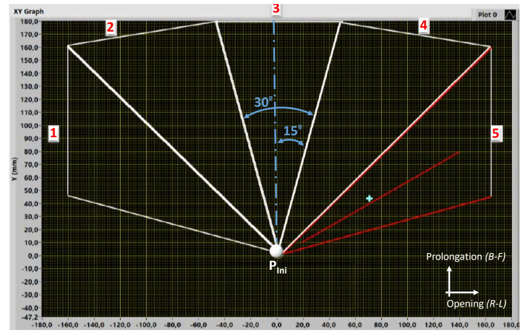

Fig. 2. Rehabilitation Software Game, where the vertical axis corresponds to the prolongation movement of the arm (Forward/Backward) and the horizontal axis with the opening movement (Leftward/Rightward).

C. Rehabilitation platform implementation

Communication between the aforementioned rehabilitation software and the UHP multifunctional robot is carried out through a low level force/motion controller. This controller calculates the torque that the motors must exert, based on the training mode selected in the rehabilitation software (passive [10] or active [20]) and the robot/user contact point motion and force measurements (Fig. 3).

In order to implement the controllers and monitor the patient, the robot integrates two encoders located in the actuation system's Maxon motors, a MINI40 force/torque sensor (ATI) to measure force in the robot/user contact point ($\mathbf{F_{Cn}}$), and a YNGS1 inclinometer (Sensor-Technik Wiedemann GmbH) to measure the motion of the contact point ($\mathbf{P_{Cn}}$). Additionally, two MPU-6000 IMUs (InvenSense) have been used to monitor the user's motion while performing the rehabilitation exercises, one to estimate the inclination angle of the body, and the other to estimate the motion of the arm.

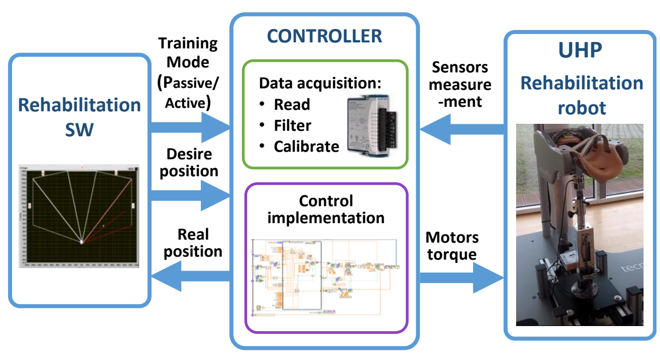

Fig. 3. Operation diagram of the rehabilitation plataform based on the UHP rehabilitation robot.

It should be noted that the controller captures the motion and force interaction between the patient and the robot during the training exercise, generating a database that allows to analyze the recovery status of the patient and adapt the exercise to his/her needs.

III. VALIDATION TEST SETUP

A. Selection of participants

In order to obtain relevant results, 25 healthy subjects, who did not have previous knowledge of the UHP multifunctional robot, nor of the rehabilitation software, were selected. The most relevant characteristics of the selected subjects are summarized in Table I.

TABLE I
MOST RELEVANT DATA OF THE PARTICIPANTS.

Participants	25	
Gender	Masculine: 18	Feminine: 7
Dominant side	Right-handed: 20	Left-handed: 5
Age	Minimum: 20 years	Maximum: 50 years
Height	Minimum: 1.63 m	Maximum: 1.88 m
Arm length	Minimum: 0.31 m	Maximum: 0.42 m

As shown in Table I, most participants are right-handed, so they have more force/movement control over the right upper limb than over the left one. Therefore, in the present work, in order to simulate a more close scenario to the one with real patients, the left arm has been selected for the execution of the validation tests.

B. Reduced mobility patients simulation

As defined in the introduction, before using the robotic device in the clinical field, it is necessary to validate it with healthy users who can support unwanted movements or forces performed by the robot. However, in order to generate a more realistic environment, several strategies have been implemented to reduce the moving range of the participants, trying to simulate a more close scenario to the one with patients with reduced mobility.

To this end, the motion range of the shoulder and the elbow has been limited using two elastic restraints. The first one is designed to encircle the body of the subject by holding both shoulders against the trunk. The second encircles the elbow, limiting its extension. Both restraints can be seen in Fig. 4.

Fig. 4. Physical restrictions of shoulder and elbow movements.

C. Design of the validation tests

In order to analyze if the UHP multifunctional rehabilitation robot complies with the requirements of users, the following tests have been proposed:

- **Test I: Movement range adjustment.** In order to avoid injuring the user, the working area of the robotic device has to be adapted to the range of motion of the user, which will depend on his/her specific physiognomy. For this purpose, with the help of a physiotherapist, the participant has performed arm prolongation and opening movements to determine his/her maximum reach range. The control algorithm of the UHP robot has memorized these maximum values and has adapted the range of motion for all the following tests.
- **Test II: Learning the game.** The objective of this test is to teach the use of the rehabilitation game and the UHP robot to each participant. For this purpose, the UHP robot has performed the game's movements in passive training mode, with a period of three seconds, while the participant has not made any effort. This allows the user to focus his/her attention to the trajectories and movements executed.

Once the participant is shown the movements to be executed to play/execute the rehabilitation game, the rest of the tests are executed in active training mode, this is, the user is the one that has to make the effort to complete the game and the UHP compensates the inertia, gravity and friction of the robot (zero force mode). This training mode is commonly implemented in the clinical field to evaluate the recovery status of patients.

- **Test III: Without constraints.** The aim of this test is to analyze the behavior of the rehabilitation platform when interacting with a healthy user. So, the participant has executed the movements without any contraint.
- **Test IV: With elbow constraint.** In this test, in order to evaluate the operation of the rehabilitation platform when the user presents elbow motion deficit, the user has executed the exercises with the proposed elbow restraint (Fig. 4).
- **Test V: With shoulder constraint.** In the last test, the shoulder restraint (Fig. 4) is used to evaluate the performance of the proposed platform when interacting with a patient with reduced shoulder mobility.

D. Execution Protocol

In accordance with the ethical regulations of Royal Decree 1716/2011, a validation test execution protocol has been defined. This way, the tests have been carried out with the presence of both a technician and physiotherapist. The first has supervised the rehabilitation platform, while the latter has ensured that the participant has performed the exercises correctly. This way, correct execution of the validation tests has been guaranteed, in addition to ensuring quick and safe response to any adversity.

Before starting the tests, the participants have been provided with a document that describes the tests to be carried out and that defines the aim of their execution. Likewise, they have been asked to sign a consent, in which they have given written permission to the use of the data obtained for scientific purposes. Finally, with the aim of detecting improving aspects, at the end of the tests, a brief questionnaire has been done.

IV. ANALYSIS AND DISCUSSION OF RESULTS

In order to validate the rehabilitation platform when interacting with different users, the aforementioned tests have been carried out with the selected 25 participants. The most relevant results are synthesized below.

A. Learning the game tests

Once the motion area of each participant using Test I is defined, the *learning the game* test has been executed. In this test, the movements have been executed by the UHP rehabilitation robot autonomously, this is, in passive training mode using a position based controller.

In Fig. 5 the results of two participants with totally different physical features are depicted. *Participant A* has a medium movement area with a range of $0.160m$ in the prolongation and $0.155m$ in the opening moments, while *Participant B* has been the user with the highest range of motion ($0.180m$ in both directions). In both cases, in blue the desired ($\mathbf{P_{Cn_{Des}}}$) and in green the actual position of the point of contact ($\mathbf{P_{Cn}}$) in the plane xy are observed.

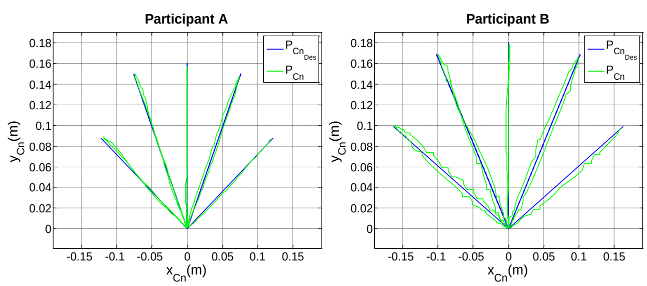

Fig. 5. Results of the test in passive mode with two healthy users.

Table II summarizes the mean and maximum position error of both tests.

TABLE II

POSITION ERROR IN PASSIVE MODE WITH TWO HEALTHY USERS.

Participant	Mean error	Maximum error
A	$0.0312m$	$0.088m$
B	$0.0411m$	$0.099m$

As it can be seen, the designed game has been correctly adapted to the range of movement of each participant, generating position references ($\mathbf{P_{Cn_{Des}}}$) that depend on the maximum range of each one. For example, in region 3 (vertical line), the UHP robot has moved from the initial position to the maximum range of each user in the prolongation movement ($0.160m$ for the *Participant A* and $0.180m$ for the *Participant B*).

On the other hand, it was observed that the rehabilitation platform has not generated any sudden and inappropriate movement that could injury to the user, making movements in a smooth and safe way. This behaviour has been observed for all 25 participants. In addition, although all subjects have tried to prevent the movement of the rehabilitation robot, the UHP has completed the trajectories in the selected period of three seconds with a mean error lower than $0.0411m$ (Table II).

B. Tests with and without motion constraints

Once the ranges have been adjusted, and the participants have familiarized with the robot, the behavior of the rehabilitation system when the participants executed the movements has been analyzed. For this purpose, three tests in active training mode have been executed. In the first ones, the participant has performed the exercise without any constraint, in the second, the movement of the elbow has been limited, and in the last one, the movement of the shoulder has been constrained.

In all tests, to verify that.the rehabilitation platform behaves properly, the force ($\mathbf{F_{Cn}}$) and the position ($\mathbf{P_{Cn}}$) of the contact point have been analyzed. Additionally, in order to determine if the users have executed the exercises correctly, the inclination of the body and the upper limb has been studied.

Analysis of the contact force

Fig. 6 details the force of the robot/user contact point ($\mathbf{F_{Cn}}$) of *Participant C* in the aforementioned tests. In the first plot the results of the test *without constraints* are depicted, in the second the results of the test *with elbow constraints* are detailed, and in the last one those of the test *with shoulder contraints* are observed. Blue colour corresponds to the force of the contact point on x (Fx_{Cn}) axis, while green is related to y (Fy_{Cn}) axis.

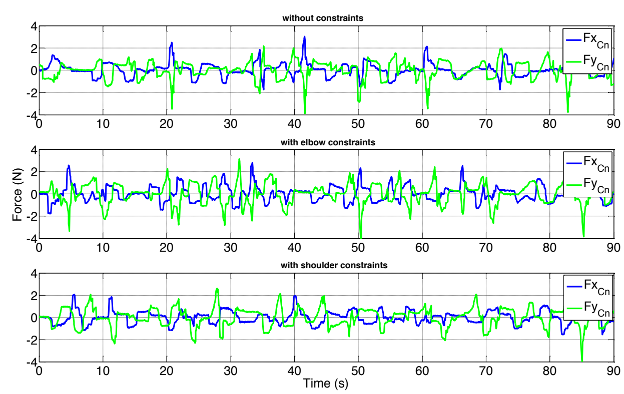

Fig. 6. Force of the contact point $\mathbf{F_{Cn}}$ with and without restrictions with the *Participant C*.

Results show that, for all participants, including the one shown in Fig. 6, the force mean error has been less than $1N$. In addition, the UHP rehabilitation robot has never executed high forces that could injure the participant; in the worst case, the maximum contact force has been less than $5N$.

Likewise, it can be seen that the rehabilitation platform presents similar performance in the tests executed without and with constraints. That is, the rehabilitation platform has behaved appropriately and safely when interacting with healthy people and with participants who have simulated movement deficit of the elbow and shoulder.

Analysis of the motion of the contact point

Fig. 7 details the movement of the contact point ($\mathbf{P_{Cn}} = [x_{Cn}\ y_{Cn}]^T$) of *Participant C* in the three tests. The first plot shows the results of the test *without constraints*, the second shows those *with elbow constraints*, and in the last those *with shoulder constraints* are detailed. The desired position is depicted in blue ($\mathbf{P_{Cn_{Des}}}$) and the actual position of the point of contact ($\mathbf{P_{Cn}}$) in the plane *xy* in green. Red lines indicate the maximum range of motion for each test when the participant has not been able to complete the movement.

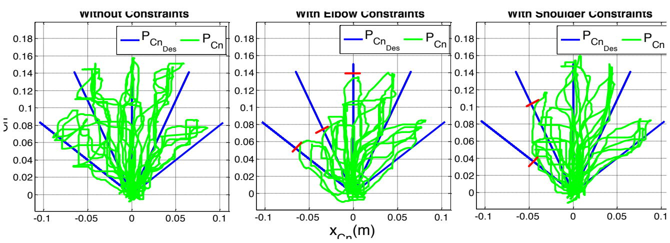

Fig. 7. Motion of the contact point $\mathbf{P_{Cn}} = [x_{Cn}\ y_{Cn}]^T$ with and without restrictions with the *Participant C*.

In these tests, the UHP has not prevented the movement executed by the user, allowing the participant to perform the exercise in a safe way. It can be seen that, as shown in Fig.7, that in general the participants have performed better the middle zone sectors (2, 3 and 4), as the reachability of the limb is higher, and the motion is simpler (less arm aperture). However, it is clearly seen that the use of restraints to simulate impaired limbs has an important influence on the reachability of the participants. In fact, sectors 1 and 2 present very low reachability compared with the others (as stated by the red line), due to the fact that the participant has not been able to reach the final point. Hence, measuring the reachability and range of motion of patients before performing the exercises is critical to setup properly the robotized therapy.

Analysis of the inclination angle of the participant

Finally, the body motion of the participants is analyzed. For this purpose, two IMUs have been attached to the back of the patient and its arm. This way, trunk inclination and arm motion can be estimated. Based on these values, knowing the position of the robot and the physical characteristics of the subjects (height and arm length), the position of the elbow and shoulder have been estimated. And from this estimation, the contribution of the body to each movement has been obtained. This is, the percentage of the movement executed with the upper limb, and the percentage executed by the body (for instance, if the participant bends forward instead of elongating the arm).

In the previous section it has been concluded that sectors 1 and 2 are the trajectories that present lower motion range when restraints are applied (Fig. 7). For this reason, in order to observe the contribution of the body, results of these two sectors are analyzed.

TABLE III
PERCENTAGE OF THE MOVEMENT EXECUTED WITH THE UPPER LIMB.

Test	Region 1		Region 2	
	x	*y*	*x*	*y*
Without restrictions	97%	106%	92%	101%
With elbow restriction	73%	104%	85%	112%
With shoulder restrictiono	70%	100%	87%	107%

Table III shows the average percentage of the movement executed with the upper limb on the axes *x* and *y*. As it can be seen, without movement constraints, the obtained values are very close to 100%, which means that most of the movement has been executed with the upper extremity. However, with the restraints, on the *x* axis, the percentage decreases, indicating that users have used the entire body to execute the trajectory. This confirms that patients with reduced mobility tend to use the body to help the movement of the upper limb and increase their reaching ability. Therefore, in order to ensure that patients perform the exercises properly, the inclination of the trunk and of the upper extremity must be measured.

C. Acceptance Questionnaire

From the analysis of the tests, the correct and safe operation of the rehabilitation platform has been verified when interacting with users with different physical characteristics. However, in rehabilitation applications, in addition to this, it is essential to evaluate the opinion of the participants, as an user who feels insecure when interacting with the robot will reject its use.

Therefore, in order to analyze the opinion of the users and detect aspects of improvement, a questionnaire has been filled out by the participants at the end of the validation tests. Five areas have been evaluated by the participants, using a three degree scale: 1) Disagree; 2) Partly agree; 3) Agree. Table IV summarizes the results of this questionnaire.

TABLE IV
EVALUATION OF THE 25 PARTICIPANTS.

Question	**1**	**2**	**3**
I have known what I should do	0	0	25
I have been able to follow the indications	0	3	22
I felt calm when interacting with the robot	0	4	21
I have felt safe when:			
The robot was responsible for the movement	0	2	23
I was responsible for the movement	0	1	24

Table IV details that all the participants have been correctly informed of what they should do at each moment, and that most of them have been able to follow the indications, there have been only 3 of 25 participants that have presented issues when operating the robot. Hence, an important percentage of users have understood the use of the rehabilitation software and the UHP multifunctional robot with the indications given by the technician responsible for the test and the physiotherapist.

Also, it is observed that most of the participants have felt calm when interacting with the rehabilitation robot. Only 4 of them have indicated that they are partially in agreement with this statement, while the remaining 21 have indicated that they fully agree. Likewise, almost all users have felt safe when they have been responsible for the movement and when the movement has been performed by the robot. Hence, the rehabilitation platform transmits tranquility and security to the user.

In summary, with the execution of the validation tests, the correct and safe operation of the rehabilitation platform based on the UHP multifunctional robot has been verified when interacting with users with different physical characteristics. From the analysis of the results it has been observed that the robot has been able to generate smooth and safe movements. The robotic device has not generated sudden movements or high forces that could injure the user. Additionally, these conclusions have been ratified thanks to the opinion of the participants, who have claimed to have felt calm and safe when interacting with the rehabilitation platform.

V. CONCLUSIONS

In order to validate the safety and robustness of the robotic device and verify that it complies with the needs of users, it is necessary to perform a pre-clinical validation with healthy users.

In this work, the validation of the UHP upper-limb rehabilitation robot is detailed. For this purpose, a set of different validation tests have been designed and implemented with a group of 25 participants. Additionally, in order to limit the range of motion of users and simulate patients with reduced mobility, some movements restraints have been designed.

Results show that the rehabilitation platform behaves properly with healthy people of different physical characteristics. The rehabilitation game has been correctly adapted to the range of motion of each participant, and the UHP multifunctional robot has not generated sudden movements or high forces that could injure the user. These conclusions have been ratified thanks to the opinion of the participants, who have claimed that they have felt calm and safe when interacting with the rehabilitation platform.

Validated with a group of healthy people, further experiments with actual patients who have different level of impairments will be a future interesting topic in order to ensure clinical adaptation and acceptance of the rehabilitation platform based on the UHP rehabilitation robot.

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