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A Virtual Reality System for Robotic-Assisted Orthopedic Rehabilitation of Forearm and Elbow Fractures

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***Abstract*— The combination of robotics and virtual reality seems promising for the rehabilitation of the upper limb by promoting intensive training on specific deficits with motor control and multimodal feedback in engaging game-like scenarios. In this paper we present the integration of a robotic system and virtual reality applications for the orthopedic rehabilitation of the arm, in terms of strengthening training and motion recovery. The system simulates the upper limb of the patient and their actions, and allows exhaustive exercising and motor control, giving visuomotor and haptic feedback and trajectory positioning guidance. The system allows assign specific tasks to perform within the virtual environments and aids to evaluate the mobility condition of the patient, to personalize the difficulty level of the therapy and provides kineseologic measures of the patient evolution. We present the results of a preliminary clinical assessment we are carried out on three patients in order to assess the usability and acceptance of the system.**

I. INTRODUCTION

The articulations of the human wrist, forearm and elbow may suffer severe lesions causing bone fractures. The symptoms include swelling, pain and functional disability. In cases where the fracture is stable and without dislocation of fragments, a cast or a splint made of thermoplastic material is used for external immobilization. Fixation includes the upstream and downstream joints of the fractured zone and ensures the immobility of the lesion area. An unstable and dislocated fracture requires a surgery intervention of reduction and stabilization and the following immobilization with a cast or a splint [1]. The rehabilitation treatment generally tends to start as early as possible, in order to avoid posttraumatic rigidity at the joints, contracture formation, for recovering the normal range of motion (RoM), muscular strength and the daily-life activities.

Three main techniques of manual therapy for motion recovery can be mentioned: 1) Passive exercising are used when the subject cannot move at all his own limb; such training is important to maintain flexible joints and prevent joint contracture. 2) Active exercising is performed when the patient has control of any limb part without external assistance; the active exercising helps to improve joint flexibility and muscular endurance. 3) The active-assisted exercising is preferred if the muscles are weak and cannot perform all of the work on its own, until the subject gains control and strength of his own muscles.

In recent years, several studies have shown some advantages of robotic-aided therapies if compared to conventional therapies in stroke patients [2], [3], [4], [5], [6]: the repetitive motor activity is performed with higher level of motor control, allows to increase the duration and number of the sessions, can give variable assistant or resistant force feedback to the patients while performing motion tasks, and can provide online objective information of the patient performance. Virtual Reality (VR) applications on the other hand, can render multimodal feedback while patients perform physical training therapy that involves perceptive and cognitive functions, promoting the patient's interest and motivation, by assigning engaging activities in several conditions. Moreover, the complexity of the therapy can be progressively increased according to the personal condition of the patient [7], [8].

Despite that the use of robotic and virtual reality technologies in stroke rehabilitation have spread quickly in the past years, the use of such technologies for orthopedic rehabilitation has received little attention and very few studies have been reported. In [9] Schwickert et al., 2011 reported a pilot study which proved the feasibility of robotic-assisted rehabilitation of proximal humerus fractures in virtual environments.

In this paper we present a platform for the orthopedic rehabilitation of the arm mobility after forearm and elbow fractures. The system consists of a six degree of freedom (DoF) robotic arm, (three actuated), in conjunction with a VR simulation model of the human upper limb for assisting passive, active and active-assisted range of motion and strength recovery. The system allows the patients interact within physics-based simulated virtual environment (VE) scenarios and provides multimodal feedback during the execution of motion tasks. Patients received visuomotor feedback by observing in first-person perspective the reproduction of his/her arm movements and actions in the screen, at the time that received force feedback while the user is handling and manipulating the robotic arm.

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II. ROBOTIC SYSTEM FOR THE ARM ORTHOPEDIC REHABILITATION

A. Robotic Device

The robotic rehabilitation device, called BRANDO (Figure 1), derived from the adaptation of a haptic interface we developed in the past [10] into a 6 DoF mechanism mounted into a stable and mobile platform.

The first 3 DoF are actuated and track the position of the end-effector (EE) in space (within a box workspace of $600x400x500mm$). They consisted of the combination of two orthogonal and incident rotational joints, and a prismatic joint that drives a barrel along a third incident axis. The first 2 DoF are actuated through a differential transmission composed of two capstans acting on a common driven pulley. This mechanism allows high kinematic isotropy along x and z directions, and high regularity of the mass matrix properties. The actuation was made by three brushed DC motors with iron-less construction of the rotor; the first two motors were grounded in order to reduce the amount of moving mass, while the third motor provides the translational motion of the barrel. In order to minimize as possible the backlash, no reduction gear was employed in the design. The last 3 DoF are passive and represent a spherical joint that allows track the orientation of the handle mounted on the EE. The handle includes two sensorized buttons (on the frontal and top sides), in order to let the patient to trigger simple commands during the interaction.

Two weights are fixed to the rear of the barrel, acting as counterbalance of its weight in the central position of the device workspace.

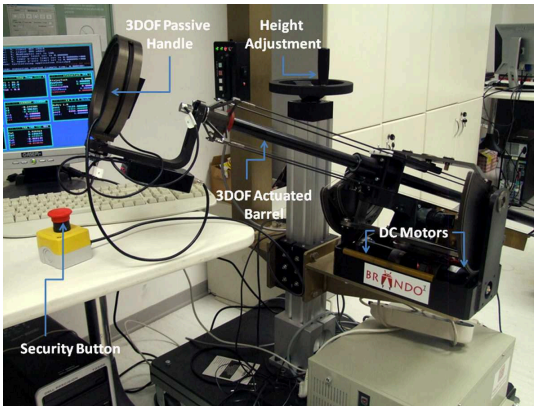


Fig. 1. BRANDO system: the robot device mounted on the mobile platform.

The robotic arm and the control unit are mounted in a platform consisting of a mobile base with 4 restraining wheels and a balancing column. The column is a 2 DoF's passive arm that allows to balance the patient arm weight through an industrial tool (with a maximum payload of $4kg$).

B. Virtual Reality Upper limb simulation

Motion therapies are highly embodied activities where multisensory processing is involved. Thus, rendering multimodal feedback that leads the self-body perception of the patient seems very useful for facilitating the motor skills (re)learning or recovery by involving the patients in meaningful embodied activities and tasks [11]. Therefore, incorporating virtual humanoid avatars that naturally replicate the patient's movements while they are acting in realistic simulated environments seems significant for promoting in patients the perception of their own movements and improvements [12], while experiencing simulated real-life situations [13] through the awareness sensation that such external body representations are part of their own bodies [14].

With these motivations we developed a realistic VR model of the human upper limb and integrated to the robotic device. The model is composed by a multi-body rigid dynamic system, with a 7 DoF serial mechanism for the arm [15] and 17 DoFs with 18 limbs for the hand [16], in form of revolute joints. The model simulates in real time the upper extremity of the patient and the physical interaction with the virtual objects, providing visual and proprioceptive feedback of the patient's arm movements. The model was implemented on the VR software platform XVR [17] and in C++ using the nVidia PhysX SDK for the physics simulation.

C. Control Scheme for Patient-Robot Interaction

The control scheme was implemented at two levels and applied to the robot device during the execution of the training tasks, as illustrated in the architecture on Figure 2.

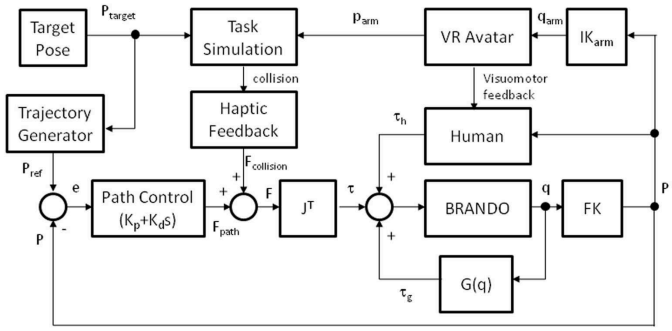


Fig. 2. Block of diagram of the control architecture for the task simulation through FE elbow movements. P is the position of the end-effector that represents the wrist of the patient in the real space; $\mathbf{P_{arm}}$ is the position of the wrist of the avatar in the VE; $\mathbf{P_{target}}$ is the target end point position of the virtual object to manipulate; e is the total error; K_p and K_d are the proportional and derivative control coefficients; F_{path} is the control force rendered by the impedance control scheme; $F_{collision}$ is the force derived from collisions between the upper limb model (VR Avatar) and the target virtual object; $G(q)$ computes the gravity compensation torque; FK is the direcet kinematics block; $\mathrm{IK_{arm}}$ is the inverse kinematics algorithm of the patient arm.

The low level controller runs on the Target Unit (TU) which is a real-time system composed of: 1) an xPC single board industrial PC; 2) a data acquisition board (DAQ) to acquire the encoders values and commanding the motors of the robot; 3) three linear driver's that convert the DAC's signals into the appropriate electrical currents to drive the motors; 4) four buttons to manage the status of the robotic device. The control algorithm of the robotic device performs the forward kinematics of the robot, the gravity compensation

algorithm and the low level state machine to manage every operational phase.

The high level controller relies on the Graphic Unit (GU) running on a graphic workstation which contains: 1) the implementation of the virtual scenarios; 2) the physical simulation engine and the state machine for controlling the task simulation; 3) the target pose selection and the target trajectory generator; 4) the path control algorithm and the haptic controller. The communication between the TU and GU for exchanging and updating control data (position and orientation of the end-effector, forces and control parameters) is achieved via UDP.

The GU selects the target virtual object in the virtual environment; then the virtual position of the target object is transformed into the target position in the cartesian space. Since the passive handle mounted in the end-effector is not actuated, the end-effector orientation is ignored in the definition of the target pose. Then, a minimal jerk reference trajectory is generated from the starting end-effector position towards the target position [18].

Positioning the patient wrist is done by a PD controller giving the proportional (K_p) and derivative control coefficients (K_d) (Figure 2). In particular, the impedance value K_p is adjustable by the therapist on the range of $[0, 1]\ \frac{Nm}{rad}$, while the damping coefficient K_d is proportional computed to keep on the ratio $\frac{K_p}{K_d}$ always constant; such ratio has been determined empirically during the preliminary tests. During passive or active-assisted training, the resulting haptic forces are exerted when the robot is working for assisting the patient to follow the reference trajectory in the space. For the active training, the generated force field can be applied against the patient motion by pushing the robot end-effector to the middle position of the workspace [5], in order to supply resistive forces in the opposite direction of the movements of the patient.

Haptic collision forces are the reacting forces computed by the simulation when the virtual hand gets in contact with some virtual object. These forces can be enabled or disabled by the state machine of the task simulation depending on the virtual task to perform, for example when the task is to touch a virtual object; haptic collision forces are also generated as a result of the introduction of additional constraints by setting up some static objects in the VE.

In order to increase transparency and make the robot more compliant, a feedforward compensation of the weight of the moving links of the robot has been implemented on the low-level control. This helps the patient to avoid carrying on the load and feeling the weight of the device.

Finally for safety reason, manually locking the end-effector position by the therapist is also possible at any moment. This is also useful for cautiously registering the motion limits of the patient at the beginning of the session.

III. ORTHOPAEDIC REHABILITATION OF FOREARM AND ELBOW FRACTURES

Two VR training applications for the recovery of the elbow and forearm motion were created, following a clinical-centered design. Two exercises from manual therapies were selected: the flexion/extension (FE) of the elbow and the pronation/supination (PS) of the forearm. The applications have implemented different VR scenarios and depending on the scenario, the patient is requested to complete different activities during the execution of the selected series of exercises.

The system includes a graphic user interface (GUI) for managing the parameters of the sessions, according to the specific patient condition. With the GUI the therapist controls several aspects of the therapy, including: the registration of the patient condition (RoM, the joint angular velocity and the tolerated haptic force intensity); personalizing the training sessions; tracking the performance of the patient in terms of the score and the achieved difficulty level; monitoring kinematic information of the patient, in terms of achieved RoM, velocity of motion and the time for completing the task; having graphical reports and statistics of the patient evolution; and managing the database of the patient.

A. Elbow Strengthening Training and RoM Recovery

For the elbow recovery, the selected exercises corresponded to flexion/extensions at the elbow with the arm adduced to the body. The respective activity comprises the repetitive task of reaching a target object in the scenario by positioning the robot end-effector at the corresponding target space position. The simulated activity consisted of the task of touching and ringing a bell with the index finger ($Bells$ game, Figure 3.a).

The first part of the session comprises the evaluation of the personal characteristics of the patient in terms of the elbow's FE motion capacity. Initially with the help of the GUI the therapist set up the dimensions of the patient's arm. Next, the therapist registers the motion condition of the patient, defined by $\mathbf{M}\left(ROM, \bar{\dot{q}}_4, \dot{q}_4^{peak}, t_{base}, K_p, F, \right)_{patient}$ in the following order:

1) The starting range of motion ($RoM_{patient} = \left[q_4^{FLEX}, q_4^{EX}\right]$) of the patient within the angular limits of the flexion q_4^{FLEX} and extension q_4^{EX} movements;

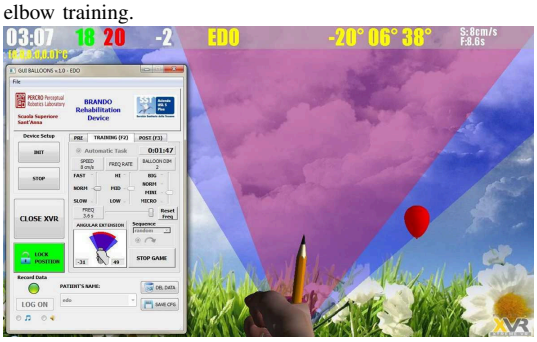
2) The mean and peak angular velocities, $\bar{\dot{q}}_4$ and $\dot{q}_4^{peak}$ at the elbow joint within the registered $RoM_{patient}$. Additionally, the minimum timeout t_{base} required for completing the movement in the full $RoM_{patient}$ at the $\bar{\dot{q}}_4$ angular velocity.

3) The tolerated amplitude of the interaction force that the robot will exert during the training. For estimating the force amplitude F needed for completing the FE movements in the amount of time t_{base}, the therapist manually adjust the corresponding impedance gain K_p of the controller, in a way that the observed elbow velocity match approximately a value within $\left[\bar{\dot{q}}_4, \dot{q}_4^{peak}\right]$. For safety, the values of K_p must be incrementally tuned up within a range of $[0, 0.2n]\ \frac{Nm}{\circ}$, where $n = 1 \ldots 10$ is the n iterative test applied by the therapist on the GUI.

In order to motivate the patient to perform challenging movements, to sustain the patient's attention and to promote

the patient's interest, the therapist can modify during the session the difficulty level of the training by manually adjusting in the GUI the game parameters, as follows: 1) setting up the game workspace RoM_{work} within the range of $[1.0, 1.5]$ times the registered $RoM_{patient}$; 2) the size of the virtual objects; 3) the timeout t_{task} for completing the task within the range of $[0.5, 1.5]$ times the t_{base} value; 4) the number of objects in the workspace; 5) the sequence of appearance of the objects at random position or, at the RoM_{work} limits; 6) the haptic forces by assigning an impedance gain within the range on $[-0.5, 1.0]$ times the registered gains, where positive values indicates assistance forces and negative values indicates resistive forces.

(a) Game application and a view of the therapist GUI for the elbow training.



(b) Game application and a view of the therapist GUI for the wrist training.

Fig. 3. Training game scenarios with the implemented tasks.

B. Forearm RoM Recovery

For the arm recovery, the selected exercises corresponded to the PS of the forearm with the elbow flexed at (90^o) with the arm adduced to the body. The activity to perform during the forearm exercising consists of repetitive tasks of reaching a target object in the game by orienting the handle mounted on the end-effector at the corresponding target space orientation. In this case, the recovery of the forearm mobility is based only on performing active PS exercises, mainly involving one DoF of the handle DoF (q_5). The training is proposed as a simple game where the tasks comprise hitting with a virtual pencil every balloon that radially approach the virtual hand ($Balloons$ game), as it is illustrated in Figure 3.b.

Again, the session starts with the evaluation of the forearm PS motion capacity of the patient. With the GUI, the therapist registers the motion condition of the patient, defined by $\mathbf{M}\left(RoM_{patient}, \bar{\dot{q}}_5, \dot{q}_5^{peak}\right)_{patient}$, where $RoM_{patient} = \left[q_5^{PRON}, q_5^{SUP}\right]$) within the angular limits of the pronation q_5^{PRON} and supination q_5^{SUP}; and $\bar{\dot{q}}_5$ and $\dot{q}_5^{peak}$ are the mean and peak angular velocities of the PS.

With the GUI, the therapist can adjust the parameters of the game, in order to modify the demanding level of the tasks. In particular: 1) the game workspace RoM_{work} beyond the $RoM_{patient}$ to encourage the patient to do demanding movements; 2) the speed, size and frequency rate of arising of the balloons can be modified with the purpose of demanding precision, velocity and attention on the patient movements; 3) depending on the therapist choice, the balloons can appear in an ordered sequence, at random within $RoM_{patient}$, or farther the patient limits within RoM_{work}. Additionally, the frequency rate of the balloons raises with the increasing number score of the patient.

IV. CLINICAL TESTS

We are carrying out a clinical pilot study in order to validate the system with emphasis on its usability, acceptance and safety.

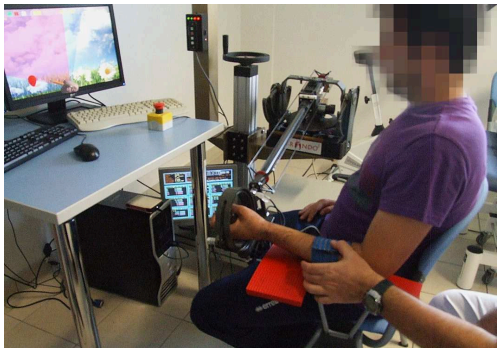
A. Patient recruitment

At the moment, three patients have been recruited to test the system who had diagnosed to follow traditional motion recovery, all reporting being right-handed: a 25 years old male patient (patient #1) with forearm reduced mobility after a dual-bone fracture at the left forearm; a 87 years old female patient (patient#2) with reduced mobility mainly at the elbow but also at the forearm due to a fracture of the humerus head at the left arm; a 66 years old man (patient #3) with reduced RoM at the forearm due to a radius fracture at the left forearm. Figure 4 shows two patients exercising for recovery motion of forearm's PS and elbow's FE.

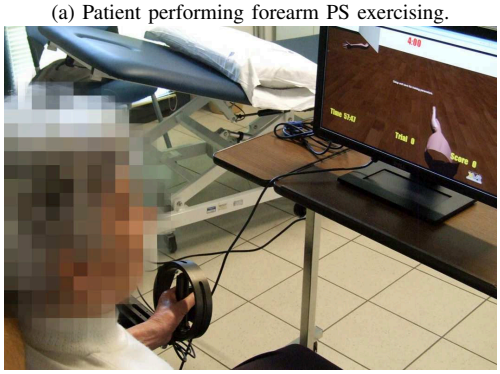
B. Experimental procedure

All three patients were naïve with the device and all undergone standard clinical tests. The RoM of the forearm's PS was measured with a wrist inclinometer (Baseline Measurement Instruments). The RoM of the elbow's FE was measured by a handheld goniometer (Lafayette Instrument Co, Inc., model 01135). The strength of the hands by the Jamar-Strength Test (JST) for measuring the maximum isometric grip strength of the hand, using a handheld dynamometer (North Coast Hand Dynamometer, USA).

Since the beginning of the tests, all patients received traditional manual therapy combined with robotic sessions one day per week. The duration of the treatment was variable among patients, until the discharge of the patients according to the criteria of the clinical staff, which in general occurs after a mean number of 30 sessions during 10 weeks. Patient #1 participated in a total of twelve weeks, patient #2 during ten weeks, and patient #3 during five weeks. The robotic assisted sessions lasted for 30 minutes. All patients were asked to perform both, forearm and elbow training with the system within their motion capabilities.



(a) Patient performing forearm PS exercising.



(b) Patient performing elbow FE exercising.

Fig. 4. Patients performing robotic assisted rehabilitation of the arm under the supervision of the therapist.

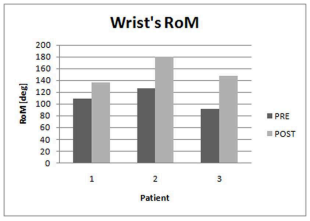
Patient #1 and patient #3 underwent RoM recovery treatment for the forearm, while patient #2 underwent therapeutic sessions for RoM recovery at the forearm, and with emphasis on the elbow. However, all three patients were asked test both gaming applications $Balloons$ (for PS of the forearm) and $Bells$ (for FE of the elbow). All patients were informed about the system characteristics and the aim of the sessions we carried out always under the supervision of the clinical staff at the USL5 Rehabilitation Centre at Fornacette(Pisa), Italy.

V. CLINICAL RESULTS

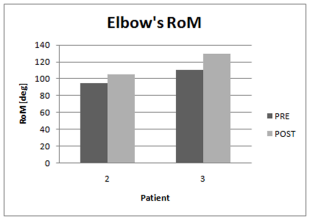
Three clinical metrics were considered for evaluating the progress of the patients, since the beginning until the end of the protocol: the RoM of both the elbow's FE and the forearm's PS; the strength level of the affected hand (S); and the strength ratio between the affected and healthy sides (S_{ratio}=[0,1]), from 0 (absence of any registered strength level on the hand of the affected side) to 1 corresponds to a symmetrical strength capability between both, the affected and healthy hands. Scaling of 0.1 was applied on the strength ratio, considering that dominant hand is 10% stronger than the non-dominant one [19].

The values of RoM of PS forearm's movements, S and S_{ratio} were evaluated in all three patients; while the RoM of FE's elbow movements was just evaluated in patient #2 and patient #3, because patient #1 did not present any mobility difficulty at the elbow.

As shown in Figures 5 and 6, all three patients presented significant enhancements in all the corresponding metrics. The observed forearm RoM of patient #1 presented an acceptable enhancement (109° before, to 137° after the treatment); presented also a slight increment of hand strength S (from $14kg$ to $19kg$ before and after the treatment, respectively) and also in S_{ratio} from 0.30 to 0.44. Patient #2 presented an enhancement in forearm RoM (from 126° until all the anatomical range of 180°) and an increment in elbow RoM (95° before and 110° after); in JST patient #2 presented a moderate strength enhancement from practically no grip capability from $S = 0kg$ to $S = 5kg$, and a two-hands strength ratio of S_{ratio} of 0 to 0.225. The measurements in patient #3 also shown acceptable progress, from 92° to 148° in forearm RoM and an enhancement in elbow RoM from 105° to 130°; patient #3 doubled his hand strength capacity from $16kg$ to $29kg$ in S and 0.30 to 0.61 in S_{ratio}. The post-intervention observed outcomes for the RoM were above the reported functional RoM for daily-life activities, of 100° for both elbow FE [20] and for forearm PS [21]. The reached strength of three patients was still below the reference values of healthy population [22], but this usually needs more time than the duration of the treatment [9]. Finally, we qualitatively observed that all patients understood well the tasks and verbally expressed to enjoy the training and had felt motivated.

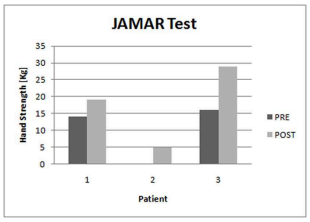


(a) Observed RoM of PS forearm's movements of all three patients.

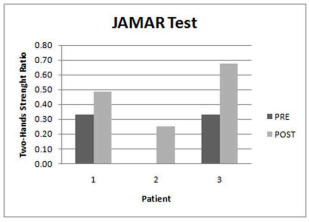


(b) Observed RoM of FE elbow's movements of patient #2 and patient #3.

Fig. 5. Range of Motion (RoM) measured values, before and after the rehabilitation treatment of the patients.



(a) Observed strength S of the affected hand.



(b) Observed strength ratio S_{ratio} between the affected and healthy hands.

Fig. 6. Hand strength measured values by the Jamar Test, before and after the rehabilitation treatment for all three patients.

VI. CONCLUSIONS

We developed a robotic-VR platform for orthopedic assisted rehabilitation therapy of the human elbow and forearm. The system consisted of the integration of a 6 DoF robotic arm with 3 DoF actuated, in conjunction with a VR simulation model of the human upper limb. The system combines

the advantages of a robotic therapy with task-oriented VR scenarios with physical realism, allowing exhaustive training in engaging and stimulating environments. The system gives haptic feedback and positioning assistance and provides visual and proprioceptive feedback to the patient due to the replication of their arm movements, and information about his/her performance (score and kinematic indices).

The system includes some console software modules that allows: the registration of the patient mobility; the personalization of the therapy and the modification of the difficulty level; controlling and monitoring the training sessions; storing, managing and reporting objective and historical kinematic information of the patient evolution.

All three patients participated in the pilot experiments during all the period of the treatment, and all presented RoM and hand's force enhancements according to the performed clinical assessments. Unfortunately, for the moment is not possible to determine if the system itself was the most significant factor of such improvements, but this experience let us proof that the contrary did not occurred.

From the first to the ending session, we follow an incremental difficulty level training strategy. All patients tolerated such increments, and shown progress on their performance through the time. An interpretation is that all patients increment their confidence towards the system during the sessions, and progressively risked to perform more challenging movements. The resulting data in combination with the opinions expressed both by the patients and the clinical staff, give us confidence to conclude that the system was highly accepted. For the moment we considered that the system in its current state is useful enough for clinical research, at least for the considered cases.

Currently we are carrying on more testing experiments, in order to confirm the preliminary clinical results to confirm the usability, acceptance and safety of the system. A phase of controlled studies will be done in the short term. Future work also contemplates including some other exercises which involves more synergies of the upper limb joints and all the DoF of the system.

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