A Novel Approach for Upper Limb Robotic Rehabilitation for Stroke Patients

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Abstract. This paper presents a novel neuro-rehabilitation system for recovery of arm and hand motor functions involved in reaching and grasping. The system provides arm weight support and robotic assistance of the hand closing/opening within specific exercises in virtual reality. A user interface allows the clinicians to perform an easy parametrization of the virtual scenario, customizing the exercises and the robotic assistance to the needs of the patient and encouraging training of the hand with proper recruitment of the residual motor functions. Feasibility of the proposed rehabilitation system was evaluated through an experimental rehabilitation session, conducted by clinicians with 4 healthy participants and 2 stroke patients. All subjects were able to perform the proposed exercises with parameters adapted to their specific motor capabilities. All patients were able to use the proposed system and to accomplishing the rehabilitation tasks following the suggestion of the clinicians. The effectiveness of the proposed neuro-rehabilitation will be evaluated in an imminent prolonged clinical study involving more stroke patients.

Keywords: Robotic rehabilitation · Stroke · Virtual reality · Exoskeleton · Neurorheabilitation · Haptic feedback

1 Introduction

Upper limb motor impairment is one of the most frequent causes of long term disability following stroke. It includes muscle weakness, spasms, disturbed muscle timing and a reduced ability to selectively activate muscles. Recently, clinical trials provided evidence that the robotic therapy is effective for motor recovery and possesses high potential for improving functional independence [8,12,15]. The use of a robotic device permits to perform active and highly repetitive movements and it has been demonstrated to improve motor recovery after stroke compared to traditional therapy [2,3,7,13]. Robot-assisted rehabilitation devices

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are usually combined with Virtual Reality (VR) environment, providing physical assistance to the patients while increasing the reliability and accuracy of the treatment. The combination of robot and VR allows therapists to adjust the exercises to the specific need of each patient and to monitoring the improvements through recorded kinematics data. In order to reduce the complexity and cost issues, the robotic devices can be designed in a passive manner, only to assist the patients by gravity compensation [4]. These devices support the weight of the arm such that the patients can focus on performing the VR tasks. Recently, Comani and colleagues [5] conducted a preliminary clinical study to investigate the electroencephalography (EEG) correlating of VR exercise, using the gravity compensation provided by a passive robot. In their study motor recovery was assessed through kinematic data, clinical scales and high-density electroencephalography.

However, the passive robot assistance only focuses on the treatment of upper limb proximal segments. Rehabilitation of fingers and distal upper-limb segments is particularly relevant since these segments can compete with proximal upper-limb segments for brain plasticity when trained [14]. Our group recently proposed the design and preliminary evaluation of a robotic-assisted bilateral training system for the rehabilitation of hand grasping, that makes use of a novel robotic hand exoskeleton [11].

In this work, we present a novel VR-based rehabilitation system which integrates the use of an active under-actuated hand exoskeleton with the TrackHold passive robot, which provides adjustable levels of arm-weight support. The hand exoskeleton is used to train hand movements and modulate the grasping strength. The VR games provide different exercise scenarios, where the patients are asked to perform reaching tasks while connected to Trackhold. The novelty of our system, compared to [5], is to provide a grasping movement under the assistance of the active hand exoskeleton, assuming to render a more realistic feedback to the patients with disabilities throughout the rehabilitation therapy. Furthermore, other VR-based exercises, which involve specifically the use of the grasping force, were added. In the envisaged physical therapy setting, the patients can train both the modulation of the grasping force through a robot assisted bilateral approach, and the reaching and grasping functionalities through the arm weight compensation and hand movements assistance. All the VR-based exercises have been developed together with clinicians in order to match the requirements of usability by the patients and to be a functional training for activities of daily living (ADL). In particular, tasks are focussed on improving the eye-hand coordination and on regaining the fine modulation of grasping strength. System performance has been previously evaluated within a group of 4 healthy volunteers, assessing its general usability and performance in replicating the grasping force, and successively with two stroke patients to assess the feasibility of its use in stroke rehabilitation. A clinical trial involving more stroke patients is currently underway to investigate the efficacy of the proposed system in terms of motor recovery measured through physiological test, clinical scales, and motor outcomes.

2 Materials and Methods

The proposed system, depicted in Fig. 1a, is composed of (I) the hand-exoskeleton for assisting the hand grasping, (II) a passive manipulator (TrackHold from Kinetec, [10]) for position tracking and gravity compensation of the arm, (III) the graphical user interface (GUI) with the VR rehabilitation and evaluation games, and (IV) two graspable objects equipped with pressure sensors. Each part of the system is detailed in the following subsections.

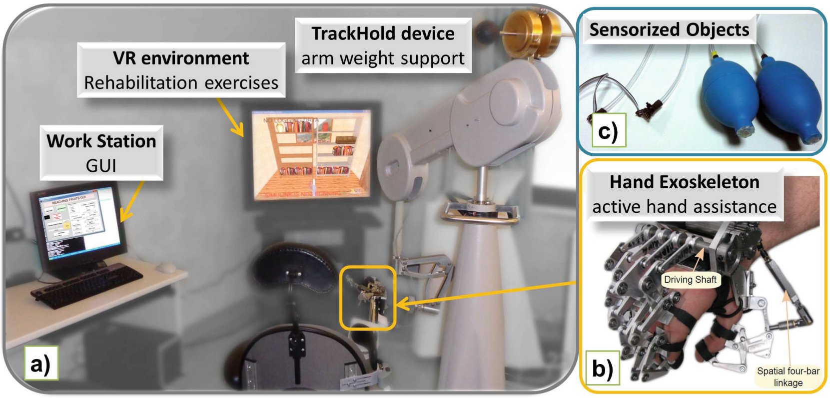

Fig. 1. (a) The distal and proximal upper limb rehabilitation system (b) Detail of the hand exoskeleton (c) The grasping force sensors.

2.1 TrackHold

The TrackHold (distributed by KineteK Wearable-Robotics) is a pure passive rehabilitation device for training the upper limb. It features seven degrees-of-freedom (DoFs) that mimic kinematics of the shoulder, elbow and wrist with a considerable available workspace (70 × 40 × 40 cm). The device is able to compensate for the effect of gravity by providing arm-weight support with adjustable counter-weights. The angular position of each joint of the device is measured by Hall-effect sensors, providing full information of the position and pose of the hand using the inverse kinematics. The sensors are connected to the host PC via USB with a sampling frequency of 100 Hz.

2.2 The Hand-Exos

The Hand-Exos, as depicted in Fig. 1b, is a two DoFs active hand orthosis with a particular design capable of adapting the mechanism to different hand sizes. The device is conceived to support post-stroke patients during grasping tasks of cylindrical objects, with one DoF dedicated to the actuation of the thumb, and another DoF to the combined actuation of the fingers. The device is composed of five planar mechanisms, one for each finger, located on the finger dorsum, not to interfere with the real objects while grasping. Human finger segments are integrated with the kinematics of the device in parallel, with each planar mechanism. This results into intrinsic adaptability of the exoskeleton to different hand sizes. The proportional voltage-torque transfer function was implemented as a feed-forward control algorithm, receiving the torque reference as input and applying the resulting voltage to the motors by Pulse-Width-Modulation. The algorithm was computed on compact electronic boards (Pololu jrk motor controller), one for each actuator, integrating both a micro-controller (PIC18F14K50) and a MOSFET H-bridge (MC33926). Each board received the torque reference (25 Hz refresh rate) through USB communication with the host PC. The torque reference was computed on a host PC depending on the rehabilitation exercise (see Sect. 2.4). For a detailed description of the kinematics of the Hand-Exos and of the control mechanism see [11].

2.3 The Sensorized Graspable Objects

Two sensorized graspable objects have been introduced for measuring the grasping force exerted by both the healthy and the impaired hands. Similarly to the devices presented in [11], the sensorized objects have consisted in two identical rubber air blower pumps, equipped with two pressure sensors (MPX4250A, range 20-250 kPa; sensitivity 20 mV/kPa, see Fig. 1c). With such design, the grasping forces have been evaluated in terms of pressure, achieving more robust measurements to variations of contact points between the fingers and the grasped object. Output of the sensors has been sampled at 100 Hz, with 10 bit resolution, and sent to the host PC through USB connection.

2.4 The Virtual Reality Scenarios

The virtual scenarios of the rehabilitation system consist of 3 rehabilitation games and 3 evaluation exercises. Games and exercises involve reaching-grasping tasks and modulation of grasping forces. A user-friendly GUI has been designed for the therapist to control the parameters and the phases of the exercises. By means of the GUI, the therapist can control the basic functions of the rehabilitation games, such as start and stop, position offset of the hand and the overall difficulty levels. For each rehabilitation exercise there are four difficulty levels (from easy to expert) each involving a specific set of game's parameters. In the default using of the GUI the specific parameters controls are disabled. However, the expert therapist could access to this control button enabling the advanced user GUI. Description of each rehabilitation game and the evaluation exercises is reported in the following paragraphs.

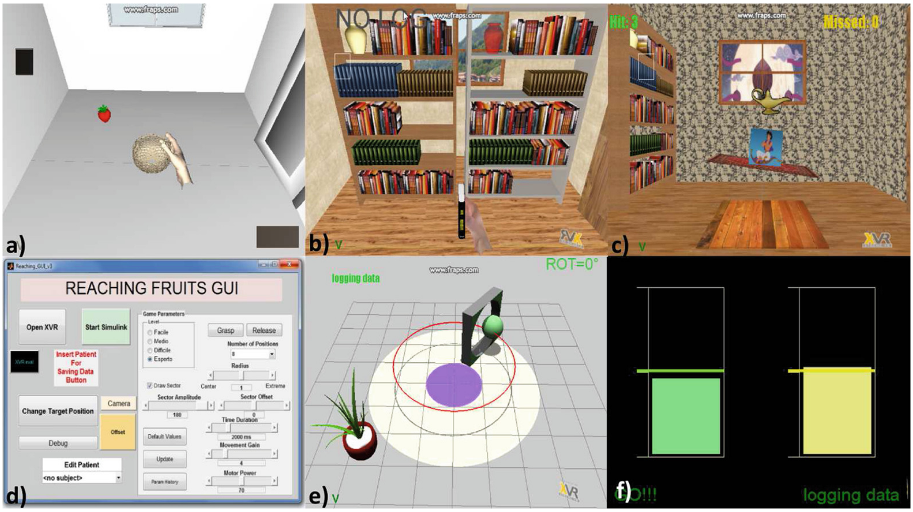

Fig. 2. The developed virtual scenarios: (a) the "Basket" rehabilitation game based on pick-and-place. (b) the "Bookshelf" based on a modified pick-and-place paradigm. (c) the "Magic Carpet" game involving modulation of the grasping force. (d) Sample view of the GUI for easy control and parametrization of the rehabilitation games. (e) the evaluation exercise based on circular trajectories. (f) the evaluation exercise based on bi-manual modulation of the grasping force.

Virtual Scenario 1: The Basket. The first rehabilitation game is designed as a pick-and-place task where different objects, lying on the ground, has to be placed in a target basket (Fig. 2(a)). The basket is positioned, in the virtual environment, close to the rest position of the subject's arm, whereas objects to be picked appeared in different positions on the transverse plane according to the difficulty level of the exercise. During the exercise, Hand-Exos provides kinaesthetic haptic feedback of hand opening and closing. The exercise and the difficulty level is parameterized in terms of distance from the subject and the angle from the sagittal plane of the area where objects are positioned. In this game the hand exoskeleton is controlled for closing and opening automatically once the object and the target positions are reached respectively.

Virtual Scenario 2: The Bookshelf. Similarly to the previous scenario, the second rehabilitation game leads to a pick-and-place task, with the difference that the picking point is stationary whereas the releasing point is varied. Hence, differently from the "basket" exercise, the second scenario is configured as a virtual bookshelf with empty shelves to be filled with objects (Fig. 2(b)). The starting point is stationary, close to the rest position of the subject's arm, while the target position varies on a coronal plane, according to the virtual representation of the empty shelves. Difficulty level and tunable parameters of the exercise consists of the distance between the bookshelf and the subject, and positions to be reached on the coronal plane. The hand-exoskeleton control is the same of the "'The Basket"' exercise.

Virtual Scenario 3: The Magic Carpet. The third rehabilitation game (see Fig. 2(c)) focuses on the modulation of grasping forces rather than reaching-grasping exercises. In this game, an object (represented as the flying carpet, mounted by the character of the game) has to be lifted at a given height by modulating the grasping forces of both hands. Moreover, the carpet has to be lifted balanced by balancing the grasping forces between the hands, in order to prevent the character falling from it. Throughout the bi-manual operation, the patient takes benefit from the facilitation effect provided by symmetrical execution of movements [17]. In this exercise, two sensorized objects (see Sect. 2.3) are used to measure the exerted grasping forces. The robotic assistance might be activated in order to aid the balancing of forces between the two hands. In this case, the difference in the measured grasping forces are used to modulate the direction and intensity of the force applied by the hand exoskeleton, both in closing or opening of the hand.

The Evaluation Exercises. Three virtual evaluation exercises have been developed in order to assess outcomes of the motor functions involved in the rehabilitation games.

The first "reaching" exercise requires the patient to reach different positions disposed around the rest position in the virtual scenario. Trajectory error and time lapse measured for completing each reaching trial has been recorded as evaluation measurements. The second "trajectory" exercise, depicted in Fig. 2(e), asks the patient to follow a mobile reference target, travelling on a circular trajectory at constant speed in the coronal or transverse plane alternatively. Absolute position error with respect to the reference marker, and position error with respect to the circular trajectory have been measured. The "trajectory" exercise has been introduced on the basis of [9], where Krabben and colleagues have shown that circle metrics are strongly correlated to stroke severity (upper extremity part of the FM score), and have observed statistically significant differences in circle area, roundness and the use of synergistic movement patterns between healthy subjects and stroke survivors.

The third "grasping" exercise, shown in Fig. 2(f), requires the patient to grasp the sensorized objects following a sequence of reference grasping forces. Similarly to the rehabilitation game, the exercise is performed with both hands and the exerted forces are required to be balanced.

3 Experimental Methods

In order to evaluate the feasibility of a rehabilitation protocol with the proposed system, an experimental rehabilitation session was performed with healthy participants and stroke patients. During the experiment, the system was fully operated by clinicians in order to evaluate its usability better.

3.1 Participants

Four healthy subjects (aged 30 ± 5) and two chronic stroke patients with right arm hemiparesis (aged 60 and 55, upper limb Fugl-Mayer Assessment score of 12/66, and 42/66, respectively) were enrolled to take part in the experimental rehabilitation session. The unhealthy subjects met the following inclusion criteria: aged between 18 and 80 years, able to understand the study purpose and procedure, present moderate upper limb hemiparesis, MAS greater then 2. The experiments were conducted in accordance with the World Medical Association (WMA) Declaration of Helsinki [1] and all subjects provided written consent to participate.

3.2 Experimental Procedure

Each subject performed one complete rehabilitation session, the three rehabilitation games and the three evaluation exercises. During the experiment, the subject was seated on a comfortable chair in front of an LCD monitor. First, he was helped to wear the hand exoskeleton, then the TrackHold device was properly tuned to support the weight of the arm. Before the beginning of each game, the physiotherapist instructed the subject about the task to be accomplished. During the evaluation session, though the impaired limb of the patient was held attached to TrackHold device and to the hand exoskeleton, no active assistance was provided.

3.3 Robot-Based Outcome Measures

Several kinematic metrics, estimated from trajectory recordings carried out during a "trajectory" exercise, have been analysed. Trajectory isotropy has been evaluated by the estimation of the roundness, as described in Oliveira et al. [16], by calculating as the ratio between the minor and major axes of the estimated ellipse which is fitted onto the hand path. The calculated isotropy lies between 0 and 1, and a perfectly round circle yields a roundness of 1. Two other kinematic metrics have been calculated on the base of the fitted ellipse: the eccentricity, as the error displacement between both the centre of target path and of fitted path, and the tilt, representing the orientation of the estimated ellipse related to the horizontal axis. A forward and backward second-order Butterworth low-pass filter with a cut off frequency of 8 Hz was used to filter the signals from the Hall-effect sensors.

Regarding the grasping force evaluation, pressure data from both hands have been analysed. Since the task have been bilateral (e.g. the subjects have been requested to exert the same amount of force for reaching a reference target) the coefficient of determination (R^2) have been calculated between the measured grasping pressures at both hands. Deviations from the ideal linear regression (zero bias and unitary slope) are aggregated in a new performance parameter called bilateral score. Furthermore, performance parameters regarding the task have been extracted for two hands separately. These parameters are: (I) the correct trial score (a correct trial should have the mean pressure of the second half of the trial equal to the current reference values ±40 %), (II) the maximum error calculated as the maximum deviation from the reference value, (III) the Reaction time that is the time for reaching the 10 % of the maximum range performed, and (IV) the Rise Time for passing from the 10 % to the 90 % of the range performed within the trial.

4 Results and Discussion

Thanks to the user friendly software part and to the easy to wear device, all the experiment have been conducted by medical personnel with just a passive presence of an engineer. All medical personnel were instructed with a two hours demonstration one week before the beginning of the experiments. Furthermore, the medical personnel could inspect the subject performance using the GUI created for evaluation purposes. The performance of two evaluation exercises are reported for the average of healthy subjects and the patients. Regarding the grasping evaluation exercises, it emerged that, whereas for healthy subjects the R^2 values are above 0.98 with a linear coefficient close to 1 and intercept term (bias) close to zero, for patients, these values are lower highlighting difficulties in exerting the same force with both hands simultaneously. Figure 3 shows the

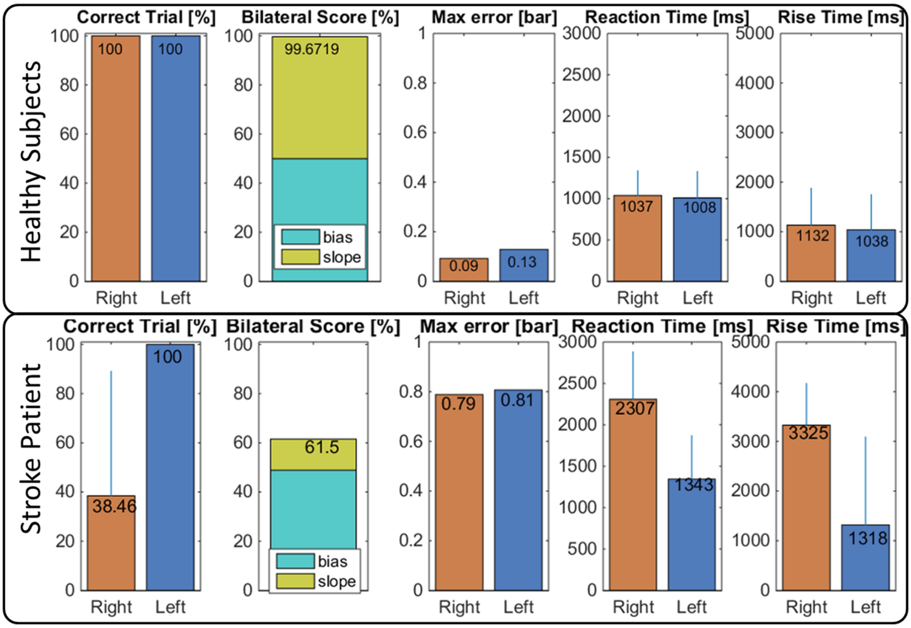

Fig. 3. Grasping pressure evaluation. The first row relates to the average of the four healthy subjects. The second row relates to the performance metrics obtained by one of the two patients. (Color figure online)

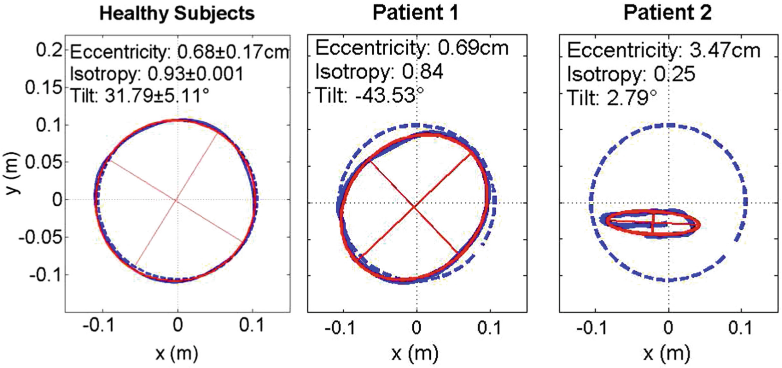

Fig. 4. Comparison of hand paths during a 'trajectory' evaluation session. Data from the averaged healthy subjects (left), and two stroke survivors with FM = 42 (middle) and FM = 12/66 (right), respectively.

performance parameters related to the Grasping evaluation game for one patient (below) and the mean of the healthy subjects (upper row). It is worth to note that the patient has shown lower performance with the affected side (right) while with the unaffected side (left) has shown performance similar to the healthy subjects.

As can be observed from the Fig. 4, the three kinematics metrics described above give a measure of the different movement abilities among a healthy subject and two patients affected by a moderate and high level of motor impairment on the right upper arm. The comparison of changes of circle metrics observed on stroke patients with values averaged over the healthy subjects can provide clear understanding about the improvement of the residual upper limb motor functions along the rehabilitation treatment. As demonstrated in several other studies [6,9], measurement of circle size and shape can provide useful information about the level of impairment of stroke patients. In fact, involving the coordination of both the shoulder and elbow joints, successful circle task represents a potentially useful movement task to evaluate multi-joint synergy. Moreover, that metrics are measured objectively and are not affected by subjective judgement.

5 Conclusion

The paper presents a novel rehabilitation system for distal and proximal upper limb neurorehabilitation after stroke. The system implements an active hand exoskeleton for assisting hand opening and closing, with an unconstrained (redundant) kinematics designed specifically for adapting different hand sizes. The exoskeleton is coupled to a passive manipulator for supporting the weight of the impaired arm and the device itself. Novelty of this work lies in the integration of the above devices with virtual rehabilitation exercises, specifically designed for encouraging proper recruitment of the residual motor functions, in congruence with the haptic feedback provided by the exoskeleton. Three different virtual scenarios have been developed, covering training in reaching-grasping tasks and in modulation of the grasping force. Development of the rehabilitation system and in particular of the virtual exercises has been carried out by a team of engineers in synergy with doctors, a physiotherapist and a psychologist, in order to benefit from different areas of expertise and better fulfil specific requirements defined by usability with real patients. The game were designed for focussing on the training of eye-hand coordination and of the grasping strength modulation that are functional to the ADL tasks. Adaptability of the rehabilitation exercises to the patient's needs and involvement of the patient in the training have been considered as the key factors during the development of the presented system. To this purpose, the virtual exercises have been implemented in terms of rehabilitation games, and a full parametrization of the exercises has been possible for the therapist through an intuitive graphical user interface. Feasibility of the proposed protocol is evaluated through an experimental rehabilitation session performed with a control group of four healthy subjects and two chronic stroke patients. In order to better evaluate the usability of the system as a rehabilitation tool, all the experimental sessions were conducted directly by clinicians. The system showed to be easily operated by the medical personnel and adjusted to the different requirements of subjects and patients. All the patients were able to complete the proposed rehabilitation games reporting no disease or fatigue. Moreover, patients verbally reported that a pleasant sensation in feeling opening/closing their impaired hand on cue. Thanks to these promising results, the rehabilitation protocol will be initialized using the proposed system to evaluate the efficacy of the method, in terms of motor outcomes after a longer period of rehabilitation. A clinical trial involving stroke patients is currently underway to investigate the efficacy of the proposed system as a rehabilitation tool.

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