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Changes were made to this version by the publisher prior to publication. The final version is available at http://dx.doi.org/10.1109/TMECH.2014.2353298.

A mechatronic system for robot-mediated hand telerehabilitation

Mario Cortese*[1], Marco Cempini*[1], *Member, IEEE*, Azzurra Chiri[1], Paulo Rogério de Almeida Ribeiro[2],
Surjo R. Soekadar[2], Maria Chiara Carrozza[1], *Member, IEEE,* Nicola Vitiello[1,3], *Member, IEEE*

***Abstract* — This paper presents a novel mechatronics master-slave setup for hand telerehabilitation. The system consists of a sensorized glove acting as a remote master and a powered hand exoskeleton acting as a slave. The proposed architecture presents three main innovative solutions. First, it provides the therapist with an intuitive interface (a sensorized wearable glove) for conducting the rehabilitation exercises. Second, the patient can benefit from a robot-aided physical rehabilitation in which the slave hand robotic exoskeleton can provide an effective treatment outside the clinical environment without the physical presence of the therapist. Third, the mechatronics setup is integrated with a sensorized object, which allows for the execution of manipulation exercises and the recording of patient's improvements.**

In this paper, we also present the results of the experimental characterization carried out to verify the system usability of the proposed architecture with healthy volunteers.

***Index Terms* — Telerehabilitation, wearable, robotics, hand, exoskeleton, home assistance.**

I. INTRODUCTION

FOLLOWING a disabling event such as a neurological or orthopedic injury, patients are leaving hospitals and returning to their homes sooner than in the past [1], even if they need prolonged rehabilitation. Evidently, this category of patients can greatly benefit from physical telerehabilitation that allows them to remotely receive assistance, without the burden of going to the hospital on a daily basis. This becomes more important for patients living in rural areas, away from the hospital, but still requiring prolonged sessions of mobilization of the impaired effectors.

Over the last two decades, the concept of systems for physical telerehabilitation has been approached by both academic and industrial research teams [4], [5]. The desired paradigm is to provide rehabilitation therapy in the patient's home, without sacrificing the quality of the treatment, and to monitor the patient's progress through web facilities.

State-of-the-art systems for telerehabilitation can be primarily classified into two categories. The first one includes those systems that allow patients at home to independently perform functional exercises by means of a PC, often running a virtual reality (VR) environment or a video game, and wearable tools for capturing the kinematics and kinetics of the motion and provide a feedback, e.g. sensorized gloves or hand exoskeletons [2], [3]. This category includes computer-based biomechanical evaluation tools used for monitoring the rehabilitation process, such as the Eval system, developed by Greenleaf Medical (Portola Valley, CA, US) [4], [6], or the evaluation tools developed by Lafayette Instrument Company (Lafayette, IN, US) [7]. Within this framework, a representative case of study is the PC-based telerehabilitation system proposed in [8], [9] by Popescu *et al.*, that is comprised of a VR environment, a force feedback glove called the "Rutgers Masters", and a series of networked PCs. The patient can perform both physical and functional exercises at home, while the remote PC records, stores and analyses rehabilitation progress. Heuser *et al.* [10] employed still the RutgerMaster for a proof-of-concept of a post-surgery telerehabilitation, but being the device deployed on the user palm, it did not allow grasping of real objects: instead a VR tool was used to simulate interaction. Reinkensmeyer *et al.* [11], [12] presented the so-called "Java Therapy": a computer joystick with force feedback that allowed patients to practice simple movements using web-based rehabilitation. Another interesting platform is presented by Yang *et al.* [13], [14], where a PHANToM™ haptic device (Geomagic, Wilmington, MA, USA) is used by patients to interact with VR environments in a game-like format during rehabilitation sessions. Golomb *et al.* [15], [16] presented an extensive study on VR telerehabilitation for children based on the use of 5DT Data Glove (5DT Inc., Irvine, CA, US), which detects finger flexion/extension and JAVA3D custom games. A common feature of all of the above telerehabilitation scenarios is that recorded data are analysed remotely by the therapist, who can in turn modify the complexity of the rehabilitation exercise.

While providing proof of the relevance of telerehabilitation paradigms for home physical exercises, the above systems do not allow the therapist to have direct, real-time (RT) control or feedback on the mobilization of the impaired articulations. Indeed, despite a minor burden of work for the therapist, whose main role is to analyze patient progress and set the parameters of the rehabilitation therapy, the above platforms

Manuscript submitted on October 1, 2013. This work was supported in part by the European Union within the WAY Project FP7/2007-2013 under Grant Agreement 288551 and the CYBERLEGs Project FP7/2007-2013 under Grant Agreement 287898; Regione Toscana under the Health Regional Research Programme 2009 within the EARLYREHAB Project; and the Italian Ministry of Economic Development within the AMULOS Project under contract MI01_00319.

[1] The BioRobotics Institute, Scuola Superiore Sant'Anna, 56025 Pontedera, Pisa, Italy (email: m.cortese@sssup.it, m.cempini@sssup.it, n.vitiello@sssup.it, a.chiri@sssup.it, carrozza@sssup.it). M. Cortese is the corresponding author.

[2] Applied Neurotechnology Lab, Department of Psychiatry and Psychotherapy and Institute of Medical Psychology and Behavioral Neurobiology, Eberhard Karls University Tübingen, Germany (email: paulorogeriocp@gmail.com, surjo.soekadar@uni-tuebingen.de).

[3] UO Riabilitazione Cardiaca, Fondazione Don Carlo Gnocchi, Via di Scandicci snc, 50143 Florence, Italy

*Authors equally contributed to the work.

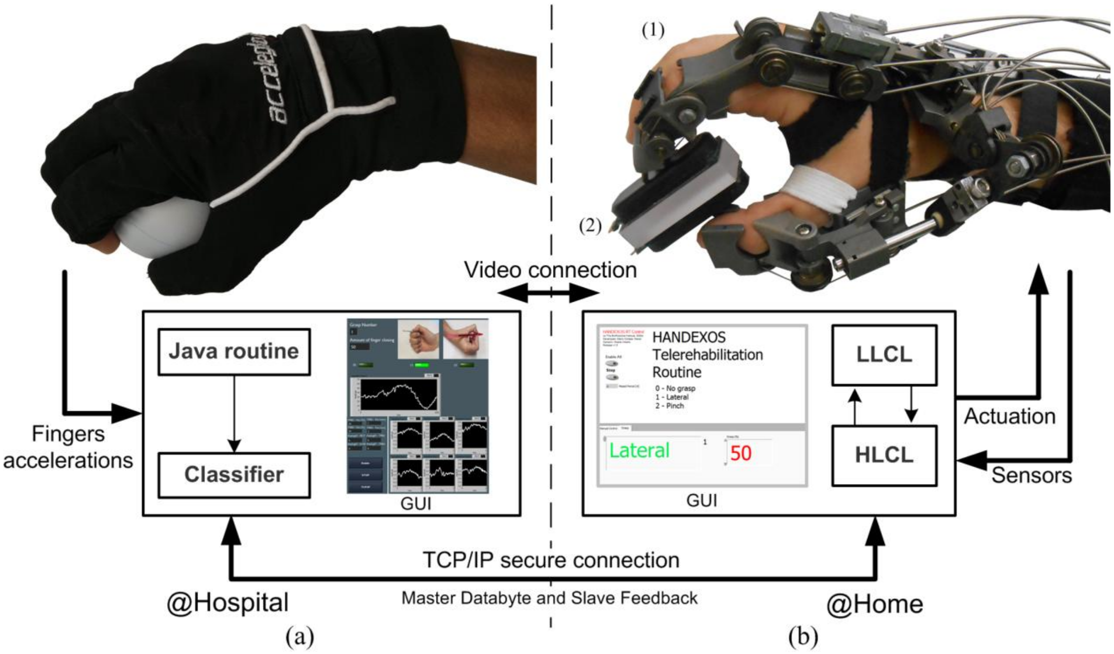


Fig. 1. Overview of the master-slave telerehabilitation system. (a) Master unit: Acceleglove worn by the therapist. (b) Slave unit: (1) the hand exoskeleton worn by the patient and (2) the sensorized object.

relay on the capability of the subjects to autonomously execute the training exercises.

The second category of state-of-the-art devices addresses the cases in which the patient still requires strong supervision from the therapist to accomplish the rehabilitation exercises, often recurring in subjects after a stroke or affected by apraxia. These devices were indeed proposed to establish a RT-direct link between the therapist and the patient. An example is the system designed by Holden *et al.* [17], [18] where a training-by-imitation rehabilitation strategy is supervised by the therapist, who can change the speed and pause the virtual “teacher” on the patient’s screen. Another interesting system is presented by Durfee *et al.* [19], [20]. Patients have to follow a fixed track on the screen with the movements of their fingers. The therapist interacts by voice and video with the patient in real-time and remotely controls the rehabilitation session by changing the parameters and the shape of the track.

A particular group of telerehabilitation devices belonging to this second category consists of master-slave setups. In this case, the master unit records the intended motion in real-time, and the therapist can guide the patient’s impaired limb along a desired motion pattern, immediately adjusting the task parameters as needed, based on the RT feedback from the patient. One of these systems was proposed by Song and Guo, which showed how a therapist can guide the patient arm – attached to an anthropomorphic robotic arm – along a desired motion pattern, through a haptic interface PHANToM™ (Geomagic, Wilmington, MA, US) [21]. Another master-slave system was presented by Peng *et al.* [22] for the treatment of elbow hypertonia at home and by Duong *et al.* [5] for upper-limb function recovery.

In this paper, we introduce a novel mechatronics master-slave setup for hand telerehabilitation (Fig. 1). The goal of the system is to enhance the physical rehabilitation of patients with hand impairments in either acute or sub-acute phases of injury, such as post-stroke survivors and subjects affected by apraxia.

The proposed system design combines three independent devices for enabling as many important features for the telerehabilitation, making it innovative over existing systems. First, the therapist is able to guide the impaired hand during a desired rehabilitation exercise by means of an *intuitive interface*, i.e., a sensorized wearable glove. Second, the slave unit is a robotic hand exoskeleton. On the one hand, a robotic artefact is employed in the telerehabilitation scenario in order to benefit from the *robot-aided physical rehabilitation paradigm*, which helps and supports physicians in providing high-intensity and repetitive therapy of the impaired limb [23]-[27]. By “high-intensity therapy” we refer to the fact that the therapist is not executing the whole force required for the task, but only drives the slave unit by mean of the master glove: this kind of interface is more intuitive and less demanding for the therapist himself. These robots allow patients to receive a more effective and stable rehabilitation process, and therapists to reduce their workload. On the other hand, we opted for a powered exoskeleton for the following reason: despite a higher system complexity, exoskeletons can provide assistance at the level of each joint into a same human body limb, and directly addresses an enhanced retraining of the correct physiological skeletal-muscle synergies, minimizing and controlling for any compensatory movements [28]-[30]. Furthermore, being wearable, exoskeletal robots can record the user’s motion without any additional motion tracking systems. Third, the mechatronics setup also comprises a *sensorized graspable object*, which allows to record the grasp force during the execution of manipulation exercises.

In this paper, we also present the results of the experimental characterization carried out to assess the suitability of the proposed master-slave architecture with healthy volunteers as they manipulated sensorized objects. An extended abstract of this work was previously presented in a conference proceeding [31], where we gave a concise overview of the design paradigm.

This paper is organized as follows. The design and implementation of the telerehabilitation setup are described in Section II. Protocol and results of the experimental characterization are described in Section III. System architecture and performance are discussed in Section IV. Finally, we draw conclusions in Section V.

II. TELEREHABILITATION PLATFORM

This section presents the main technical solutions of the master-slave telerehabilitation apparatus. After a brief overview of the system, we describe the three subsystems that were implemented in the mechatronics apparatus (namely master unit, slave unit, and sensorized object) and the communication protocol to address telerehabilitation exercises.

A. System overview

An overview of the proposed mechatronic setup is shown in Fig. 1. It is composed of three main units:

1) the *master unit*, which consists of a sensorized glove worn by the therapist and which provides on-line records of the intended rehabilitation exercises;
2) the *slave unit*, which consists of a powered hand orthosis (a robotic exoskeleton), whose development was based on the design principles illustrated in [32], and on the early prototype presented in [33]. A detailed description of the kinematic chain and model of the exoskeleton is given in [34]-[35];
3) the *sensorized object*, which consists of a plastic parallelepiped endowed with soft pressure-sensors.

The master and slave units are connected by means of a bidirectional link. On one side, the master unit records, processes and classifies the therapist's motion, and sends the motor commands to the remote slave unit in real-time. On the other side, the master receives feedback from the slave unit on the kinematics and kinetic state of the exoskeleton, as well as of its interaction with the sensorized object. A personal computer (PC) is equipped with a graphical user interface (GUI) giving information on current state of the master and slave systems as described in Section II.E to both parties. Information from the GUI allows the therapist a real-time monitoring of the rehabilitation task, with the possibility to adapt the protocol as like as he/she would be present.

B. Master unit

The master unit consists of two modules: the commercial sensorized glove Acceleglove (AnthroTronix, Silver Spring, MD, USA), which tracks the motions of the therapist's hand, and a custom Java routine, which processes the glove output data and extracts the motion command for the powered hand exoskeleton running on a PC.

The Acceleglove is equipped with six 3-axis MEMS accelerometers, one for each finger and one for the back of the palm. The output of each accelerometer is a three-component vector $\vec{a} = [a_x \quad a_y \quad a_z]^T$ (range: ±1.5 g, sensitivity: 800 mV/g, sampling rate: 120 Hz). With reference to Fig. 2(a), when the palm is parallel to the desktop, the *z*-axis is parallel to the gravity vector, while *x*- and *y*-axes lay in a plane perpendicular to the gravity vector. For the development of the proposed telerehabilitation apparatus, we used the output variables from three out of six accelerometers (i.e. the accelerometers placed on the thumb and the index finger are actually used for the execution of the task whereas the one on the back of the palm is used only in the calibration-offset phase).

Fig. 2. Master unit. (a) Reference system and kinematic variables of Acceleglove. (b) Therapist hand in the three admissible configurations. (1) "Rest". (2) "Pinch". (3) "Lateral grasp".

Data from accelerometers are converted in position vectors $\vec{p} = [p_x \quad p_y \quad p_z]^T$ for each accelerometer and classified by means of a custom Java routine implementing a two-stage decision tree.

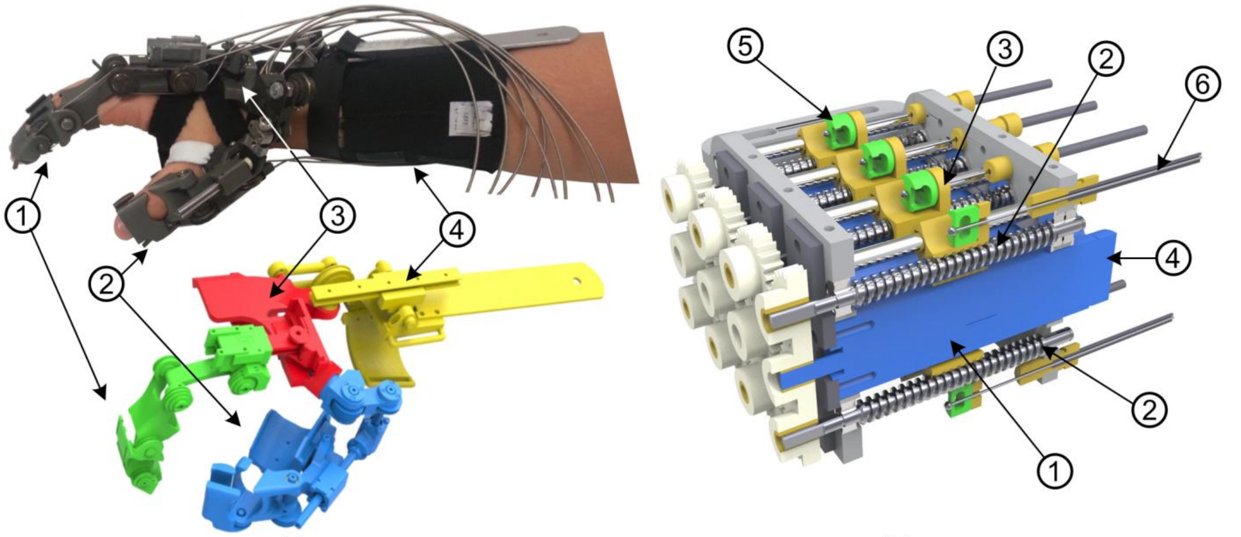
First, data are processed to recognize the manipulation task the therapist wants the patient to execute. Each motor task is commanded by means of a different hand posture (HP). Three cases are considered (see Fig. 2(b)):

1) *Rest*, this is the case when the therapist does not want to command any motion task;
2) *Lateral grasp*, for commanding the execution of a 2-digit lateral grasp;
3) *Pinch grasp*, for commanding the execution of a 2-digit precision pinch task.

The above three HPs are identified by comparing p_x^{in} and p_x^{th} - respectively of the index finger and thumb - with pre-defined thresholds (namely $\hat{p}_{Rest}$ and $\hat{p}_{Grasp}$) which were chosen by the therapist during calibration of the master system prior to the protocol:

$$\begin{cases} \text{if } p_x^{in} < \hat{p}_{Rest} \text{ and } p_x^{th} < \hat{p}_{Rest} \text{ then HP is 'Rest'} \\ \text{if } p_x^{in} > \hat{p}_{Grasp} \text{ and } p_x^{th} < \hat{p}_{Grasp} \text{ then HP is 'Lateral'}. \\ \text{if } p_x^{in} > \hat{p}_{Grasp} \text{ and } p_x^{th} > \hat{p}_{Grasp} \text{ then HP is 'Pinch'} \end{cases} \quad (1)$$

Second, for the HPs 'Lateral grasp' and 'Pinch grasp' we also calculated two variables, P_L and P_P, which expressed the



(a) (b)

Fig. 3. Slave unit. (a) Overview of the hand powered exoskeleton (1). Index finger module. (2) Thumb module. (3) Palm module. (4) Forearm module. (b) Actuation-transmission system. (1) Gear-head DC motor. (2) Antagonistic screws. (3) Sliders. (4) Magnetic incremental encoder. (5) Tendon cable force sensor. (6) Bowden cables.

percentage of grasp accomplishment. Both P_L and P_P change from 0 to 100% with the therapist gradually executing either a lateral or a pinch grasp:

$$\mathrm{P}_L = 100 \cdot \frac{\left(p_y^{in} - p_{y,\mathrm{min-lat}}^{in}\right)}{\left(p_{y,\mathrm{max-lat}}^{in} - p_{y,\mathrm{min-lat}}^{in}\right)} \tag{2}$$

$$\mathrm{P}_P = 100 \cdot \frac{\left(p_y^{in} - p_{y,\mathrm{min-pin}}^{in}\right)}{\left(p_{y,\mathrm{max-pin}}^{in} - p_{y,\mathrm{min-pin}}^{in}\right)} \tag{3}$$

where $p_{y,\mathrm{max-lat}}^{in}$, $p_{y,\mathrm{max-pin}}^{in}$, $p_{y,\mathrm{min-lat}}^{in}$, and $p_{y,\mathrm{min-pin}}^{in}$ are the maximum and minimum reachable values of p_y^{in} in the tasks of *Lateral grasp* and *Pinch grasp* respectively, and were identified experimentally.

C. Slave unit

The slave unit consists of a powered hand orthosis [34], [35], a mechatronic system constituted of three main sub-systems: the wearable exoskeletal orthosis for the active assistance of the index and thumb fingers; the remote actuation block attached to the orthosis by means of a cable-sheath system (see Fig. 3(a)) and the controller unit.

1) Wearable orthosis

The wearable orthosis is composed of four independent modules, conceived to allow a fast and simple don/doff procedure.

The *forearm module* is a soft cuff worn on the user's forearm: it allows for the cable-sheath to pass without crossing and gives stability to the rest of the device. It also provides a passive mechanism for wrist mobility and is adjustable.

The *palm module* is attached to the forearm module through the wrist passive chain and lays on the lateral side and dorsum of the user's hand. It is fixed to the hand by straps and elastic bands fastened to the user's palm. This module can be considered the rigid frame of the moving parts of the orthosis: here actuation cables' sheaths are capped, and the cables transmit their motion to the active degrees of freedom (DOF). From the hand module, two kinematic chains detach, the *MCP* and *CMC self-alignment mechanisms* ([32], [35], [36]). The first one allows for the self-alignment of the index's metacarpo-phalangeal (MCP) joint with the corresponding DOFs in the index module (see next paragraph), along both the flexion-extension (f/e) and abduction-adduction directions. The second one allows for active motion to be transmitted to the thumb's carpo-metacarpal (CMC) joint, allowing for the movement of opposition, while passively adapting its rotation and f/e abilities. Both mechanisms ensure adaptability of the platform to sizes of different users and are designed in order to meet the self-alignment requirements of transmitting the desired torque without fixing the hand in a static position or with undesired reaction forces [32]. Globally, the hand exoskeleton covers the phalanx lengths shown in Table I.

The *index finger module* is a finger exoskeleton that actively assists with the index finger f/e. To achieve this, a route of transmission cables is used to independently assist the MCP, while the proximal- and distal-interphalangeal (P-DIP) joints are underactuated by another single actuation unit.

The *thumb module* assists both the thumb's MCP and interphalangeal (IP) joints in the f/e task through a single actuation unit. The thumb CMC joint is actuated by another single actuation unit.

All the finger modules were conceived as rigid open shells, made of titanium in complex tri-dimensional shapes by selective laser melting manufacturing technology (SLM, CI-ESSE, Fiorano, Italy). All shells are internally covered with soft foam-like materials (i.e., neoprene) to ensure a comfortable fit, and include frictional effects to avoid the robot slippage over the skin.

Table I. Phalanx lengths the hand exoskeleton can accommodate. Distal phalanx does not have max length, since the exoskeleton shell is hollow.

	Index phalanx				**Thumb**		
[mm]	**Metacarpus**	**1**	**2**	**3**	**Metacarpus**	**1**	**2**
Min	60	20	20	18	38	29	21
Max	75	36	28		48	39	

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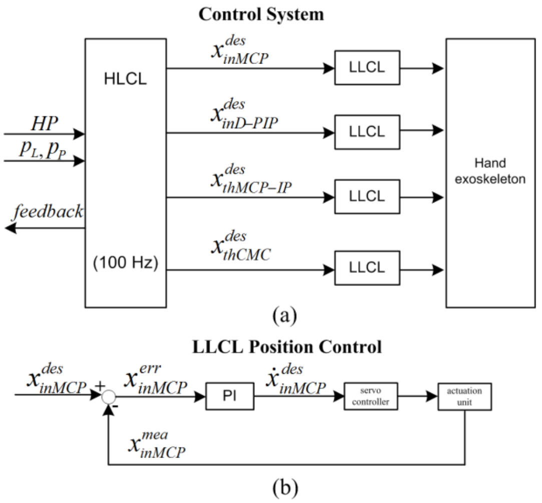

Fig. 4. (a) Overview of the slave control system where HLCL generates position commands (see eq. (4)) $x^{des}_{in\mathrm{MCP}}$, $x^{des}_{in\mathrm{D-PIP}}$, $x^{des}_{th\mathrm{MCP-IP}}$ and $x^{des}_{th\mathrm{CMC}}$ for LLCL from HP, P_L and P_P. (b) Example of the LLCL position control algorithm for the index MCP: error between desired $x^{des}_{in\mathrm{MCP}}$ and measured position $x^{mea}_{in\mathrm{MCP}}$ is converted into a desired velocity $\dot{x}^{des}_{in\mathrm{MCP}}$ for the commercial servo controller by means of PI closed-loop controller.

2) *Remote actuation block*

The hand orthosis is endowed with four active DOFs: index MCP f/e, index P-DIP f/e, thumb MCP-IP f/e, and thumb CMC opposition. All these DOFs are bidirectionally actuated, i.e. for each DOF a pair of cables is used, capable of moving in opposite direction (by pretensioning, to avoid the pushing cable to lose force), thus conveying both flexion and extension movements.

Transmission elements are nylon-coated steel wire-wrapped ropes with a gross/core diameter of 0.6/0.54 mm (Carl Stahl, Süssen, Germany), routed through flexible sheaths made of spiralized harmonic steel wire, with an outer/inner diameter of 1.6/0.8 mm (Spin Off Laboratory Company of Limited, Hokkaido, Japan). The ropes' ends are driven by means of a leadscrew (0.7 mm/revolution): for each pair of cables, two leadscrews are synchronously driven in opposite directions by a 3.11-W electrical DC motor (1331T-14:1-IE2400, Faulhaber, Germany), with a 14:1 reduction gear and an optical rotary incremental encoder. Each cable line also includes a force sensor and a Hall proximity sensor (A3213EUA-T, Allegro MicroSystems, Inc., MA, USA) that acts as limit switch for the slider's position [34]. An overview of the actuation-transmission system is given in Fig. 3(a). The antagonistic cables displacement is converted in a rotation of the active DOFs of the exoskeleton, by means of rotary pulleys, whose radii and arrangement allow the aforementioned fingers motions: details on underactuation (how driving torques split over the active joints) strategy and means can be found in [34], [35].

3) *Control system*

The control system of the hand orthosis has a two-layer hierarchical architecture (Fig. 4). Both layers run on a commercial real-time system (sbRIO-9632, National Instruments, TX, USA), endowed with both a real-time 400-MHz processor and a field-programmable gate array (FPGA) processor.

Table II. Values of $\overline{x}^{0}_{in\mathrm{MCP}}$, $\overline{x}^{0}_{in\mathrm{D-PIP}}$, $\overline{x}^{0}_{th\mathrm{MCP-IP}}$, $\overline{x}^{0}_{th\mathrm{CMC}}$, $\overline{x}^{END}_{in\mathrm{MCP}}$, $\overline{x}^{END}_{in\mathrm{D-PIP}}$, $\overline{x}^{END}_{th\mathrm{MCP-IP}}$ and $\overline{x}^{END}_{th\mathrm{CMC}}$ for the two different desired hand postures.

	Lateral grasp	**Pinch grasp**
$\overline{x}^{0}_{in\mathrm{MCP}}$ [mm]	5.7	0
$\overline{x}^{0}_{in\mathrm{D-PIP}}$ [mm]	3.92	0
$\overline{x}^{0}_{th\mathrm{MCP-IP}}$ [mm]	0	0
$\overline{x}^{0}_{th\mathrm{CMC}}$ [mm]	0	0
$\overline{x}^{\mathrm{END}}_{in\mathrm{MCP}}$ [mm]	5.7	7.98
$\overline{x}^{\mathrm{END}}_{in\mathrm{D-PIP}}$ [mm]	16.62	13.62
$\overline{x}^{\mathrm{END}}_{th\mathrm{MCP-IP}}$ [mm]	0	9.25
$\overline{x}^{\mathrm{END}}_{th\mathrm{CMC}}$ [mm]	6.08	6.8

The *high-level control layer* (HLCL) coordinates the active DOFs of the hand orthosis running on the real-time processor at 100 Hz. Specifically, it converts the intended motor task from the master (i.e., the desired HP, as well as the variables P_L and P_P) into desired position commands for the four motors (namely $x^{des}_{in\mathrm{MCP}}$, $x^{des}_{in\mathrm{D-PIP}}$, $x^{des}_{th\mathrm{MCP-IP}}$ and $x^{des}_{th\mathrm{CMC}}$, respectively for the four active DOFs: index MCP f/e, index P-DIP f/e, thumb MCP-IP f/e, and thumb CMC opposition), as follows[1].

When the intended task is *Rest*, the thumb and finger joints are fully extended: $x^{des}_{in\mathrm{MCP}} = x^{des}_{in\mathrm{D-PIP}} = x^{des}_{th\mathrm{MCP-IP}} = x^{des}_{th\mathrm{CMC}} = 0$ mm.

When the desired task is *Lateral grasp*, the thumb is opposed to the middle phalanx of the index finger. The starting point is with the index finger MCP and D-PIP joints partially flexed, while thumb MCP-IP and CMC joints are fully extended. With P_L increasing from 0 to 100%, the thumb MCP-IP joints go into opposition with the index finger MCP and D-PIP joints, according to the following set of equations:

$$\begin{cases} x^{des}_{in\mathrm{MCP}} = \overline{x}^{0}_{in\mathrm{MCP}} + \dfrac{\mathrm{P}_L \cdot \left(\overline{x}^{\mathrm{END}}_{in\mathrm{MCP}} - \overline{x}^{0}_{in\mathrm{MCP}}\right)}{100} \\ x^{des}_{in\mathrm{D-PIP}} = \overline{x}^{0}_{in\mathrm{D-PIP}} + \dfrac{\mathrm{P}_L \cdot \left(\overline{x}^{\mathrm{END}}_{in\mathrm{D-PIP}} - \overline{x}^{0}_{in\mathrm{D-PIP}}\right)}{100} \\ x^{des}_{th\mathrm{MCP-IP}} = \overline{x}^{0}_{th\mathrm{MCP-IP}} + \dfrac{\mathrm{P}_L \cdot \left(\overline{x}^{\mathrm{END}}_{th\mathrm{MCP-IP}} - \overline{x}^{0}_{th\mathrm{MCP-IP}}\right)}{100} \\ x^{des}_{th\mathrm{CMC}} = \overline{x}^{0}_{th\mathrm{CMC}} + \dfrac{\mathrm{P}_L \cdot \left(\overline{x}^{\mathrm{END}}_{th\mathrm{CMC}} - \overline{x}^{0}_{th\mathrm{CMC}}\right)}{100} \end{cases} \tag{4}$$

where $\overline{x}^{0}_{in\mathrm{MCP}}$, $\overline{x}^{0}_{in\mathrm{D-PIP}}$, $\overline{x}^{0}_{th\mathrm{MCP-IP}}$, $\overline{x}^{0}_{th\mathrm{CMC}}$, $\overline{x}^{END}_{in\mathrm{MCP}}$, $\overline{x}^{END}_{in\mathrm{D-PIP}}$, $\overline{x}^{END}_{th\mathrm{MCP-IP}}$ and $\overline{x}^{END}_{th\mathrm{CMC}}$ are respectively the starting and ending positions of the powered leadscrews.

When the desired task is *Pinch Grasp*, the index and thumb fingertips press against each other. When a command to close is received, all DOFs move according to the set of equations (4). The values of $\overline{x}^{0}_{in\mathrm{MCP}}$, $\overline{x}^{0}_{in\mathrm{D-PIP}}$, $\overline{x}^{0}_{th\mathrm{MCP-IP}}$, $\overline{x}^{0}_{th\mathrm{CMC}}$, $\overline{x}^{END}_{in\mathrm{MCP}}$, $\overline{x}^{END}_{in\mathrm{D-PIP}}$, $\overline{x}^{END}_{th\mathrm{MCP-IP}}$ and $\overline{x}^{END}_{th\mathrm{CMC}}$ differ between *Lateral grasp* and *Pinch grasp* as reported in Table II: for all joints, a 0 mm value corresponds to the corresponding joint to be fully extended (0º), while the maximum flexion (about 90º) corresponds to 10 mm for all joints but the index D-PIP, for which it corresponds to 17 mm. Extreme values in Tab. I have been chosen in order to mimic a natural grasp kinetic: in the

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[1] For sake of simplicity, for each active DOF, the motor position x refers to the linear displacement of the leadscrew driven by the corresponding DC motor and is expressed in millimeters.

lateral one, the index and thumb MCP joints do not move ($\overline{x}^{0}_{in\mathrm{MCP}}$ and $\overline{x}^{END}_{in\mathrm{MCP}}$values are the same), while the distal joints close, and the thumb CMC goes towards opposition (the index assumes a hook position, and the thumb presses over it laterally). For the pinch grasp, all the joints but the CMC close.

The *low-level control layer* (LLCL) consists of four independent PI closed-loop position controllers. It runs at 100 Hz. For each control loop, error between desired and actual position of the motor is converted into a desired motor velocity, which is controlled at 1 kHz by means of a commercial position servo controller (EPOS2 24/2, Maxon Motors, CH). The LLCL interfaces the commercial drivers by means of a CAN bus. The CAN interface runs on the FPGA processor. The FPGA processor samples at 10 kHz, low-pass filters, down-samples to 1 kHz and sends to the 400 Hz processor both the tendon-cable force sensor signals and the output from the pressure sensors of the sensorized object.

In order to prevent users from injuries and the mechatronic apparatus from possible damage, a safety loop (running at 100 Hz on the 400 MHz processor) switches off the actuation when one of the following three conditions applies: i) the force on the tendon cable exceeds 5 N, ii) motor speed is greater than 10000 rpm/s, or iii) motor current is greater than 1A. Safety is also pursued by means of a red safety button that unplugs the power supply when pressed. The actuation also is switched off if any corrupt or non-consistent data is received from the master unit. Naturally, safety measurements are also provided into the exoskeleton (see [35] for more details) as mechanical stops at the revolute joints (limiting the flexion angles in the 0-90º range) and stroke limits in the actuator unit.

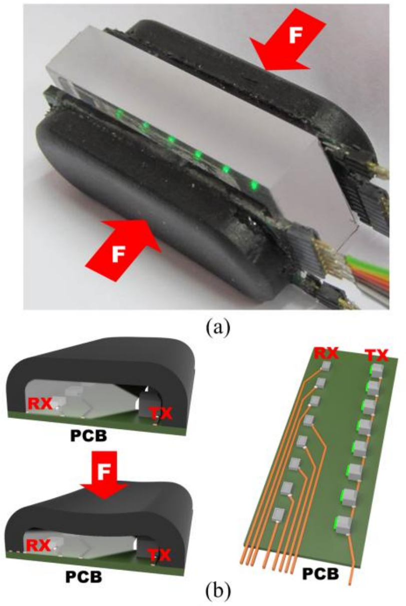
Finally, it is worth mentioning that, despite the high number of components, the slave unit is relatively compact and fits easily on a desktop or table without being an overly obtrusive presence in the patient’s home.

D. *Sensorized object*

In order to address the execution of rehabilitation exercises involving tasks of manipulation mimicking typical actions of activities of daily living, the proposed telerehabilitation scenario was endowed with a soft, sensorized object.

The sensorized object to manipulate is a rectangular parallelepiped made of acrylic resin, with the widest faces covered by two pressure-sensitive pads (see Fig. 5(a)). The size of the parallelepiped is 6x2.4x3 cm^3. Pressure-sensitive pads (PSP) are based on a sensing technology that was developed at Scuola Superiore Sant’Anna (Pisa, Italy) over the last four years, for measuring human-robot interaction forces in wearable rehabilitation robots [37]-[39].

Among the several prototypes developed over time, for the sensorization of this object, we used the first generation of PSPs (see [40] for a systematic review of this technology). Each PSP is an optoelectronic pressure sensor made of two main parts: an external silicone bulk structure, and a printed circuit board (PCB) that houses an array of sensitive elements (see Fig. 5(b)). The size of the sensor is 20×60 mm and houses an array of 1×8 sensitive elements. Each sensitive element is composed of a light transmitter, a LED (an InGaN chip technology, high luminosity green LED, OSA Opto Light GmbH, Berlin, Germany), a receiver, and a photodiode (an analog ambient light opto-electronics transducer with current output, Avago Technologies Ltd., Singapore). The silicone bulk covers the electronics components and plays an active role in the transduction principle: when a load is applied on the sensor, the cover deforms itself, the light is screened and the sensor proportionally changes its output voltage.



(a)
(b)

Fig. 5. Sensorized object. (a) Overview of the sensorized object. (b) Transduction principle and layout of the electronics board.

This sensor can measure normal forces/pressures, while it is not sensitive to tangential loads. As explained in [40], the output voltage of the eight sensitive elements of each PSP can be combined to give an estimate of the total applied force. The two PSPs can measure a maximum force of 10 N when the deformation of the silicone cover is about 1.9 mm (corresponding to a maximum pressure of 8.3 kPa, and an average stiffness of 5.2 N/mm).

The choice of using this sensor technology is motivated by a twofold reason. First, thanks to a wide sensing area, PSPs allow for the measurement of the interaction force regardless of the contact point, and therefore there is no need to endow the hand exoskeleton finger modules with sensors, thus reducing the overall system complexity. Secondly, the softness of the silicone cover can increase both the size of the contact area and the friction coefficient, thus enhancing grasp stability.

Finally, the parallelepiped was covered with PSPs on both sides in order to monitor possible abnormalities in the two-finger synergy in performing the grasp tasks.

E. *Telerehabilitation protocol*

Master and slave units are connected by means of a bi-directional link. They exchange data by means of a TCP/IP connection via a secure SSH tunnel. The communication protocol works at 100 ms refresh time, during which a data package is exchanged between the master and slave systems bi-directionally.

The master unit encodes and sends data to the slave unit about the intended motor task through a single byte. The two most significant bits bring information on the desired grasp (i.e., *Rest*, *Lateral grasp*, or *Pinch grasp*). Less significant bits

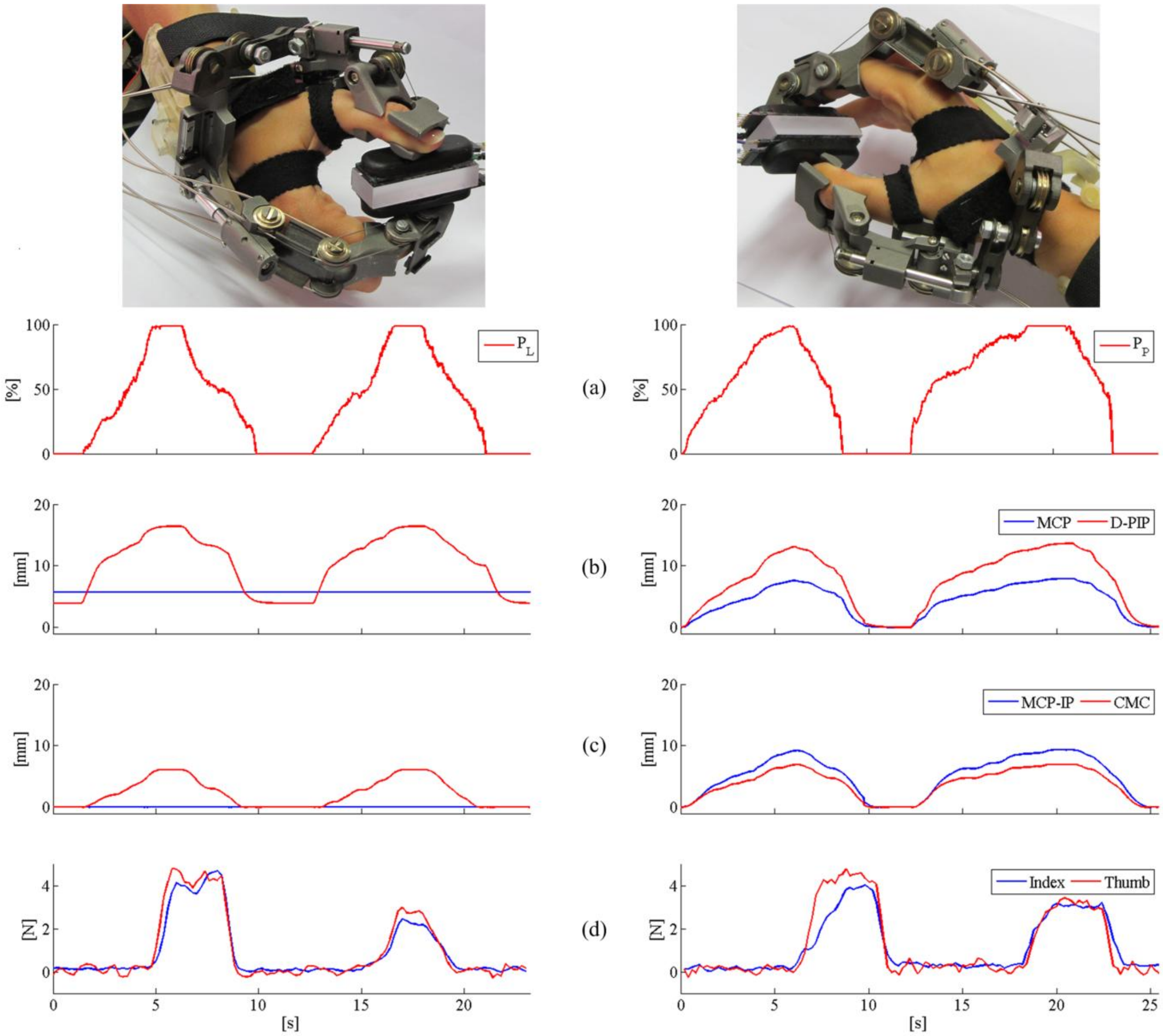


Fig. 6. Prototypical task. Left: lateral grasp. Right: pinch grasp. The panel (a) reports the closing command as sent by the master. The panels (b) and (c) report the actual motor positions of the index and thumb finger active DOFs respectively, overlapping the commands coming from the data-glove system. Motor trajectories commanded to the slave unit are proportional to data received from the master unit, as explained by equation (4). Panel (d) reports the force profiles measured by the PSPs interacting with both the index and thumb modules: it is possible to see that when the grasp is stabilized, forces reach a steady value.

encode either P_L and P_P. If the intended motor task is *Rest*, then the less significant bits encode zero.

The slave unit encodes and sends the following variables to the master unit, grouped in a single 14-byte data frame:

1) current value of each motor position: one byte is used for each motor unit; this data is proportional to the hand closure percentage, with different coefficients depending on the kind of grasp as explained in section II.C;
2) current value of total force sensed by each pressure-sensitive pad: one byte is used for each pad; this data represents the forces that the exoskeleton is able to grip the object with;
3) current value of force driven by each of the eight antagonistic tendon cables (force range: 0-5 N): one byte is used for each cable force value; the eight cable forces give an overall estimate of the resistance of the patient to the motion of the exoskeleton, in case the exoskeleton is not able to drive the user's hand till the end of the grasp.

In order to start the telerehabilitation procedure, the patient is requested to accomplish the following four-step procedure:

1) start the webcam-video channel;
2) power on the device and run a graphical user interface (GUI) on the slave unit PC: then, the system automatically executes the *homing* procedure to reset motor encoders;
3) wear the orthosis with the help of a person;
4) enable the connection with the master and thus start exchanging data; in this phase the patient will also place the sensorized object on the table, within the workspace of the hand exoskeleton, and will interact with the therapist through a webcam which shows the exoskeleton posture (identical to the hand one).

During the experimentation, through the GUI running on the local PC, the patient receives visual feedback on the intended motor task, the level of the resistive force he or she is applying and the force applied by each finger on the sensorized object. The same variables are also displayed to the therapist on the master unit PC, with additional information on the current motor positions. From an initial opened position, once the therapist starts closing the hand, the master system

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Changes were made to this version by the publisher prior to publication. The final version is available at http://dx.doi.org/10.1109/TMECH.2014.2353298.

discriminates the kind of grasp thanks to the p_x^{in} value (equation (1)), and data are sent in real time to the exoskeleton motor, obeying to equation (4).

III. EXPERIMENTAL CHARACTERIZATION

This section presents the protocol and the results of the experimental characterization of the system with healthy volunteers.

A. *Experimental protocol*

The experimental protocol was carried out with five healthy subjects (3 men and 2 women; mean age and standard deviation 27±1.8 yrs; mean and standard of index and thumb length 69.6±7.9 mm and 57.6±3.2 mm, respectively) that volunteered to test the slave device, after they provided written informed consent. Subjects wore the index and thumb exoskeleton finger modules and were instructed to relax and let the device move their fingers. During the tests, the slave unit was located in the Wearable Robotics laboratory of The BioRobotics Institute (Scuola Superiore Sant'Anna, Pisa, Italy), while the experimenter, in the role of a therapist, and the master unit were located in a laboratory of the Institute of Medical Psychology and Behavioral Neurobiology (University of Tübingen, Germany). In this master and slave unit set up, the 'therapist' defined a sequence of four grasps as a combination of pinch and lateral grasps, repeated two times each in a random order.

The test was blinded for the subjects who knew neither the typology nor the number of grasps. During the experiment, subjects were asked to not resist to the exoskeleton action and to relax. The stability of the performed grasps was verified by the force recorded by the grip sensors at the exoskeleton/tool interface.

B. *Results*

All subjects could easily wear the hand exoskeleton without reporting any discomfort in performing pinch and lateral grasps as imposed by the remote master. Furthermore, the 'therapist' could successfully drive the volunteers along the intended task in all trials: the proposed decision tree decoded the intended motor task with a success rate of 100%.

A prototypical description of both pinch and lateral grasps is reported in Fig. 6 that shows the actual values of the slider position of index and thumb leadscrews, as well as the measured force recorded by the PSPs of the sensorized object. In order to assess the repeatability of the execution of the rehabilitation tasks we measured the mean and the maximum value of the force measured by the PSPs during the execution of both a pinch or lateral grasp. Results are summarized in Table III.

Finally, experiments also revealed that the low-level position control has a -3-dB closed-loop bandwidth of 0.2 Hz and allows smooth movements of the subjects fingers. Finally, no significant delays (<100 ms) or missing data in the master-to-slave and slave-to-master communication links were reported during the experiment.

Table III. Mean and maximum force recorded by PSPs. For each subject and grasp task we reported the mean and maximum value of the force [N] recorded by each of the two PSPs; for all subjects, values are averaged over four iterations. The last column reports the values averaged across all subjects (IL: Index finger – Lateral grasp, TL: Thumb finger – Lateral grasp, IP: Index finger – Pinch grasp, TP: Thumb finger, Pinch grasp).

Subject	**#1**	**#2**	**#3**	**#4**	**#5**	**Mean ± std**
mean_{IL}	2.031	1.934	3.154	3.395	1.983	2.499±0.509
max_{IL}	3.916	3.100	4.469	4.675	3.990	2.969±0.456
mean_{TL}	3.106	2.138	3.427	3.669	2.507	3.206±0.274
max_{TL}	4.952	2.666	4.600	4.776	4.160	3.227±0.067
mean_{IP}	2.482	3.177	2.956	3.669	3.750	4.030±0.372
max_{IP}	4.665	4.850	3.960	4.018	4.935	4.230±0.85
mean_{TP}	3.278	3.445	2.851	3.094	3.470	4.485±0.215
max_{TP}	4.842	4.633	4.500	4.776	4.440	4.638±0.029

IV. DISCUSSION

This paper introduced the design of a telerehabilitation system for hand functional recovery and presented the results of the experimental activities, which aimed at assessing the system usability with five healthy subjects.

The mechatronic device and its employment in the rehabilitation trials represent the main outcomes of this paper. The hand exoskeleton mobilizes two fingers, motorizing four DOFs with a remotely placed cable-driven actuation system. Its design exploits ergonomics and self-alignment solutions, in the way the hand kinematics is driven and, as a result, its don/doff procedure has been easily carried on by all the subjects, without any reported discomfort during the motion.

Collected results also assessed that the device works in a reliable way, with a good over-subject repeatability: the slave exoskeleton can drive the human hand along the imposed path and maintain the object grasp stably, without eliciting resistance in the subject. The decoding algorithm of the master is simple, but effective and no information have been lost during the communication between master and slave.

In these kinds of telerehabilitation system, and more in general in telepresence, a strong limitation is due to time delays and loss of information, which might affect the reliability and stability: the telecommunication system must comply with some minimum standards (max. time lags, loss of information and speed). Our implementation showed good performances, since the maximum lag between the two end-points was not greater than 100 ms, and no data package was lost.

The slave control bandwidth has been sufficiently high for the proposed hand rehabilitation exercises. Stability of the grasp was mainly enhanced by two factors. First, the inherent compliance of the PSPs. The need for a compliant grasp has been showed in studies over the profile of lateral/normal forces exerted by human fingertip when picking and lifting small objects [41], [42]: a minimum amount of gripping force is necessary to accomplish the lift, and this is reflected in a deformation of the fingertip tissue. If a rigid force-sensor is employed, the contact between the exoskeleton's shells and the objects to manipulate may be unstable [43]. Second, the grasp force of the sensorized object provides a visual feedback to both the user and the therapist that increases the motivation of the patient and gives a quantitative information during the rehabilitation task. Furthermore, the compliance of the grasps also counteract the uncertainties in the flexible cable-sheath mechanical transmission, relying on a force information directly coming from the end-effector. The combination of these factors allows the therapist to guide the exoskeletal robot along motion paths resulting in interaction force profiles that are repeatable over all subjects (std of both mean and maximum force values are always lower than 20% of the value averaged across all subjects) and reach peak values which are comparable with the ones recorded in human tasks of fine manipulation [41]-[42]

As for the rehabilitation usefulness of the system, we can draw the following conclusion. Since subjects in our trial were instructed to maintain the hand the most relaxed possible, most of exoskeleton force was employed in the contact with the sensorized object. Indeed, data in Tab. II shows a very small variability across the subjects, hence they represent a reference measure of our system (exoskeleton plus sensorized object), across the grasp. In the case of an hypothetical subjects opposing resistance to the exoskeleton motion, we can foresee the two following conditions:

1. the exoskeleton is not able to fully close the fingers (overcoming the current/torque limit, stucking the rotor), so no interaction with the object is recorded. The therapist realizes it thanks to the webcam video feedback, but mainly from the discrepancy between the master glove sent data and the motor encoder position.
2. The exoskeleton can move the user's hand till the object interaction, but the force sensors show a non-stable or a very low value of the interaction force. The therapist realizes that the patient still oppose a resistance to the motion.

In our conditioned (relaxed hand) experiments, we indeed obtained the fully-passive behavior: as regard point 1, in Fig. 6 it is clearly visible a good match between the commanded and the executed motions. For what concerns point 2, in Fig. 6 it is visible the flat profile of the force once the grip is stabilized, and in Tab. II the very low standard deviation of the gripping force among different subjects.

When looking at the limitations of the proposed system, there are three main points to raise. First, it has a limited range of hand-size fitting the orthosis (which reflected in the low variability of subject’s age), but this is a well-known issue in every wearable device. Aware of this limitation, rather than the design of a “universal-to-all-size” device, we paid more attention to address the requirement of developing a master-slave system based on a portable mechatronic apparatus (most used platforms in clinical environment are ground-fixed, see [44], [45]), which could be actually usable in a non-clinical environment: this represents a real innovation in the field of robot-mediated rehabilitation techniques. Second, the hand exoskeleton has only two finger modules. Despite this feature limits the number of grasp primitives that can actually be implemented, it is still a solution to train the patient on two fundamental motor primitives, i.e. lateral and the pinch grasps: indeed, by recovering these two motor functionalities the patient can achieve a significant improvement in carrying out activities of daily living [46]. As a drawback, the employed exoskeleton is heavier than other similar devices (index and thumb models weigh respectively 118 and 151 g: a full comparison of the device with the state of the art can be found in [35]): the extra-weight are well justified by the use of self-alignment mechanisms, and the implementation of the assisted thumb opposition kinematic chain. The latter allowed to switch between the two grasps, that was unachieved in the state-of-the-art. Another limitation of the current apparatus is that the exoskeleton's actuation system is not backdrivable. On the one hand, this feature of the system limits its use to the execution of *robot-in-charge* rehabilitation tasks (i.e., the user’s hand is mobilized by the therapist movements). On the other hand, *robot-in-charge* rehabilitation tasks are highly relevant during the post-stroke acute and sub-acute phase since they can be a strategy to mitigate muscle spasticity, which is actually treated – in the standard therapy - by means of a repetitive mobilization of the impaired articulations [30], [47].

V. CONCLUSIONS

In this paper, we presented a novel master-slave system for physical robot-mediated hand telerehabilitation with three main innovative features: a sensorized glove acting as master, a robotic powered exoskeleton acting as slave and a sensorized object that recorded patient improvements. These features address important design requirements for a hand telerehabilitation system: 1) a reliable system for acquiring therapist and subject movements with a continuous exchange of data without delay or packet loss, 2) kinematic compatibility and comfort between the human and exoskeleton to ensure proper torque transmission to the subject articulations, and 3) a safe and effective system.

The proposed system design was experimentally validated with a protocol involving healthy volunteers. On the one hand, future works will be devoted to carry out a pilot clinical trial to assess the usability of the proposed system with patients. On the other hand, collected feedback from patients will be used to improve the setup in terms of higher number of active degrees of freedom (i.e., design of a module for middle, ring and little fingers) and actuation back-drivability. It will be also of interest to extend the system capabilities by including a force-based control, by using two twin sensorized objects, one grasped by the therapist, the other by the exoskeleton which attempts to reproduce the same forces.

ACKNOWLEDGMENT

The authors thank: Francesco Giovacchini, Matteo Moisé and Marco Donati for their support in the preparation of the experimental setup; Dr. Christian Cipriani and Dr. Marco Controzzi for their contribution in the development of the actuation unit; Sook-Lei Liew for her assistance in preparing the manuscript; and the team of CI-ESSE (Fiorano, Italy) for the fabrication of the exoskeleton mechanical parts.

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