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An EMG-controlled robotic hand exoskeleton for bilateral rehabilitation

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Abstract—This paper presents a novel electromyography (EMG)-driven hand exoskeleton for bilateral rehabilitation of grasping in stroke. The developed hand exoskeleton was designed with two distinctive features: (a) kinematics with intrinsic adaptability to patient's hand size, (b) free-palm and free-fingertip design, preserving the residual sensory perceptual capability of touch during assistance in grasping of real objects. In the envisaged bilateral training strategy, the patient's non paretic hand acted as guidance for the paretic hand in grasping tasks. Grasping force exerted by the non paretic hand was estimated in real-time from EMG signals, and then replicated as robotic assistance for the paretic hand by means of the hand-exoskeleton. Estimation of the grasping force through EMG allowed to perform rehabilitation exercises with any, non sensorized, graspable objects. This paper presents the system design, development, and experimental evaluation. Experiments were performed within a group of 6 healthy subjects and 2 chronic stroke patients, executing robotic-assisted grasping tasks. Results related to performance in estimation and modulation of the robotic assistance, and to the outcomes of the pilot rehabilitation sessions with stroke patients, positively support validity of the proposed approach for application in stroke rehabilitation.

Index Terms—L.3.0.l Rehabilitation; L.1 Human Haptics; I.2.9 Robotics; L.1.0.b Biomechanics; C.2.0.c Emerging technologies; H.1.2 User/Machine Systems; H.1.2.b Human-centere d computing; H.5.2.g Haptic I/O; J.3.b Health; L.3.0 Integrating touch-based interactions into various domains Assistive technology

1 Introduction

Motor impairment of upper limb function is one of the most common and challenging outcomes after stroke [1]. Common clinical deficits are prevalent in the distal upper extremities [2] with a proximal-to-distal gradient of symptoms [3], mainly consisting of loss of control over muscles (hemiparesis), emergence of muscle contractions and spasticity, disruption of coordination in motor actions, including reaching and grasping [4]. An intensive and prolonged robotic-assisted training has been shown to reduce motor impairments and positively enhance motor recovery [5], [6]. Indeed, several robotic training strategies have been successfully proposed, either based on unimanual training with desktop [7], [8], [9], arm [10], [11] and hand [12] exoskeleton devices, or bimanual training.

Bimanual training is a rehabilitation strategy based on natural inter-limb coordination [13]. Training patients with two-handed tasks improves the efficiency of grasping movements on the impaired side [14] with changes accompanied by a reorganization of brain mappings on the affected hemisphere. In fact in healthy individuals, since most of the descending and ascending pathways that connect the brain to the spinal cord cross the midline, corticomotor control of voluntary hand movements is derived from contralateral cortical areas. After stroke the role of uncrossed fibers in the brain-spinal cord pathway is remodulated [3], with a shift of the balance of limb control from the injured ipsilesional to the contralesional hemisphere [15]. For the above reasons, bimanual training has been introduced as a promising approach to stroke rehabilitation [16], [17].

Bimanual tasks require to operate the two hands together, so that they cooperate to accomplish the aimed function. Evidences indicate that the simultaneous movement of both limbs helps the neuro-muscular system to regain some stability and improve usage of the impaired limb [18], also in grasping tasks [14]. This falls within the more general bimanual "facilitation effect" after stroke [19], i.e. a facilitation of the paretic limb in the bimanual condition.

Several techniques have been proposed for bimanual training in stroke. The simplest one is the mirror therapy, where the visual illusion of the impaired limb is provided by reflection of the unimpaired limb [20]. Other approaches rely on the repetition of simple patterns of movement, such as forward/backward and left/right hand movement based on passive guidance from non-affected side (Nudelholz [21]), forearm pronation/supination and wrist flexion/extension (Bi-manu track [22]), or repetitive bilateral arm training with rhythmic cueing (BATRAC [13]) (Figure 1). Our group recently proposed a haptic bimanual system for rehabilitation training in stroke [23] encompassing more complex coordinated movements of the two hands in the horizontal plane.

However only a few previous studies have explicitly addressed bimanual training for hand grasping. Training of

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fingers and proximal upper-limb segments is particularly relevant since when trained these segments can compete with distal upper-limb segments for brain plasticity [24], while a preferential proximal treatment approach might even impede the restoration of the paretic hand and fingers. In [25] the Hand-Assist Robot for bimanual training was proposed, where the position of the paretic hand was detected with a sensorized glove, while the Hand-Assist Robot reproduced the position of the non paretic hand, but not the force.

In addition recent findings suggest the clinical rationale for usage of muscle activation as a good reference guide in bilateral training of grasping. The comparison of unimanual vs. bimanual robot-assisted conditions in arm reaching tasks has shown [26] that the initial muscle activation is more synchronized with limb motion in bimanual robot-assisted movements. Moreover similar average force and muscle activation profiles have been observed in voluntary and robot-assisted bimanual movements. So EMG captured on the impaired hand can act both as a mean to guide the impaired limb by robotic assistance during manipulation tasks, where the control of grasping force is essential, and as an intrinsic measure of the interaction force with the environment during manipulation. This approach has been recently successfully evaluated within [27] in a stroke case study, where it has been shown how contralaterally controlled functional electrical stimulation can be used to reduce arm and hand motor impairment. In this study, paretic elbow and hand extensors of four stroke patients were stimulated with intensities proportional to the degree of elbow extension and hand opening, respectively, of the contralateral unimpaired side.

Fig. 1: Existing bimanual training systems: (a) Batrac [13] (b) Nudelholz [21] (c) Bimanual Haptic Desktop [23] (d) Bi-manu track [22]

Based on the above, in this paper we propose the design and preliminary evaluation of a novel robotic-assisted bilateral training system for rehabilitation of hand grasping, that makes use of a novel robotic hand exoskeleton and on-line measurement of muscle contraction by EMG. The proposed system is devised to estimate the grasping force exerted by the non paretic hand through EMG signals, and transfer the same force in real-time to the paretic hand through an EMG-driven hand exoskeleton (Figure 2). The usage of direct EMG measurements allows to perform

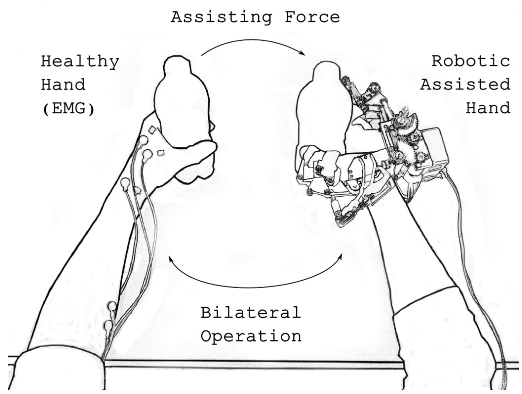

Fig. 2: The proposed bilateral EMG-based training.

rehabilitation exercises with any arbitrary object. In the envisaged physical therapy setting, the patient can modulate the force assistance provided by the hand exoskeleton to the impaired hand by adjusting the forces exerted through the contralesional hand. This bilateral approach to robotic assistance is suitable for a rehabilitation intervention since the acute phase, e.g. in patients presenting severe hand paresis with flaccidity or insufficient muscle tone: in this case, the acquisition of EMG signals directly at the non paretic limb guarantees an earlier intervention, while the impaired hand is passively guided by the hand exoskeleton. With the gradual onset of muscle tone in the recovery phase, the patient might modulate the action force exerted by the hand exoskeleton up to an assistance "as needed" level, achieving a cooperative grasping action of the impaired hand and the exoskeleton, by adapting the grasping force exerted through the unimpaired hand.

Compared to other devices for hand rehabilitation presented in literature, such as [28], a hand exoskeleton was conceived with two distinctive features: (a) kinematics allowing an intrinsic adaptability to patient's hand size, (b) capability of performing assisted grasping of real objects, preserving the residual sensory perceptual capability of touch of the hand palm. The system could provide assistance to hand grasping and finger extension in both passively guided or actively cooperating conditions. System performance was preliminary evaluated within a group of six healthy volunteers, assessing its general usability and performance in replicating the grasping force, and successively with two stroke patients to assess the feasibility of use in stroke rehabilitation.

2 The BRAVO Hand exoskeleton

The BRAVO hand exoskeleton is an active hand orthosis conceived to support stroke patients in cylindrical grasping tasks. The device has two independent degrees of freedom (DOF), one for fingers and one for thumb, for assisting grasping of cylindrical objects [29]. The hand exoskeleton is composed of five planar mechanisms, one per finger, located on the hand backside (not to interfere with object grasping) and driven by two motors, as shown in Figure 3(b). The active orthosis has been specifically developed to be integrated with the L-Exos [10], an active upper limb

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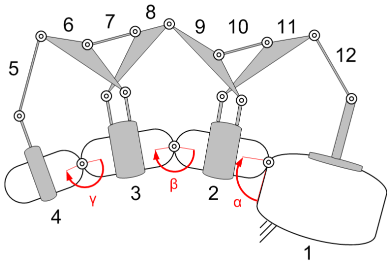
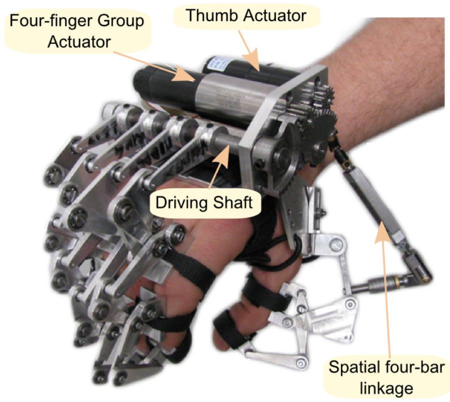
exoskeleton, so that in standard operative condition with patients, its weight (about 950 g) can be completely relieved by the arm exoskeleton.



(a) The finger mechanism, numbers indicate links



(b) The prototype v1.0

Fig. 3: The BRAVO hand exoskeleton

As for the four fingers excluding the thumb, the corresponding mechanisms are based on the same kinematic architecture [30], shown in figure 3(a). In particular each mechanism has 1 degree of freedom (DOF) for controlling the flexion/extension angles (α, β and γ in Figure 3(a)) of the human finger phalanges, whose motion is therefore kinematically coupled. The single mechanism also includes the three phalanges that are fixed to three artificial moving links (links 2, 3, and 4), through the anatomical articulations between adjacent phalanges. The four mechanisms share one common input shaft, receiving power from one actuator, thus forming a 1 DOF only "multi-finger" system.

The 1 DOF articulation was sufficient to achieve correct grasping of cylindrical objects of different size. The thumb mechanism actuates the flexion/extension movements of the two distal phalanges only. The position and the plane of motion of the thumb is adjustable through a passive 6 DOF serial mechanism and a spatial four-bar linkage (two revolute and two spherical joints) connecting the thumb links and the actuator shaft.

An intrinsic characteristic of the proposed hand exoskeleton is the straightforward adaptability to different hand sizes. Being the human segment and joints integrating parts of the mechanism, the different geometry of the resulting four 1-DOF mechanisms entails a variation in the actual configurations, in terms of relationships among the joint rotations. Data from [31] were assumed as reference finger trajectories for the design of the mechanism. Data are expressed in terms of the joint angles α, β and γ for each finger and were experimentally measured from different subjects, grasping cylinders with diameters in the range 55-120 mm. The dimensional synthesis of the mechanisms was performed considering the anthropometric data available in [32]. Changes in α, β and γ due to different hand sizes were simulated and are reported in Figure 4. Overall, the trajectory variations are always smaller than the standard deviation reported in [31], proving that the mechanism configuration exhibits a limited sensitivity to different hand sizes. Moreover, the position of the axes of driving links can be adjusted to fit with different palm widths.

As regards the performance, the hand exoskeleton was designed to exert a maximum grasping force of 30 N, considered enough to securely hold medium size objects (e.g. a glass full of water) and to contrast a possible residual spastic force of the patient during finger extension of 10 N, considered applied at the fingertip of each finger, acting orthogonal to the third phalanx middle line for every configurations along the finger trajectory [30]).

The control and driving electronics of the BRAVO hand exoskeleton were designed to be placed in a compact hardware, integrated on the hand exoskeleton, close to the actuators to reduce electromagnetic interference. During grasping, the hand-exoskeleton was considered to operate in almost isometric conditions. With low angular velocities and considering that the electrical time constants of the motors are negligible (0.033 ms), the voltage applied to the motors can be so modeled with good approximation as directly proportional to the current intensities, and consequently to the output torques. 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 main control algorithm computing the torque references from the EMG signals was implemented on a host PC.

2.1 A graspable pressure sensorized object for rehabilitation applications

A sensorized graspable object was specifically devised for quantitative estimation of the grasping force, for both the free and robotic-assisted hand. The force measurement had to satisfy the constraints of being independent of number of fingers, finger location and grasping pose. To fulfill the above requirements the cap of a 500 ml plastic bottle was equipped with a pressure sensor (MPXH6115AC6U, range 15-115 KPa; accuracy ± 1.5 KPa, see Fig. 5). Due to the thinness of the plastic walls, the empty bottle exhibited poor mechanical stiffness during compression. The cylindrical inner chamber was then filled in with water in order to increase stiffness of the object during grasping. The strength of grasping was evaluated as the

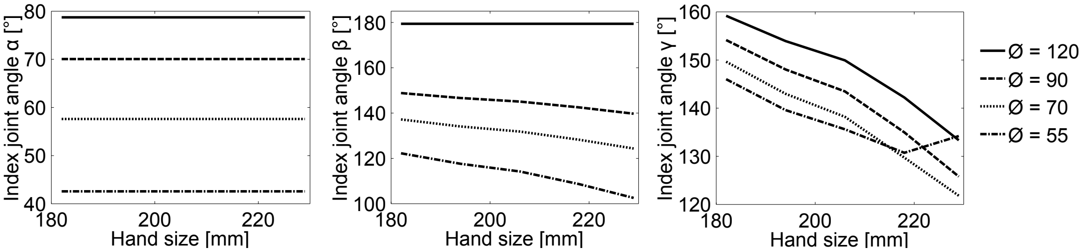


Fig. 4: Joint angle variations for different hand lengths (palm length plus finger length), when grasping cylindrical objects of diameter 55, 70, 90 and 120 [mm] respectively.

relative pressure of the fluid between the grasped object and the completely released object. Such configuration, combining a deformable surface with an incompressible liquid, assured that the pressure applied to the liquid inside the inner chamber was approximately the same impressed by fingers onto the outer surface of the device. Moreover, the whole surface of the device could be used for sensing the grasping pressure, improving the robustness of the device to variations of the fingers positioning.

Finally, in order to directly drive the hand-exoskeleton with a reference grasping pressure command, its mapping to actuators torque was estimated, by inverting the "torque to grasping pressure" characteristic. To this purpose, a stair-stepped torque reference was applied to the motors, and the resulting grasping pressure was measured through the pressure-sensorized object, as shown in top graph of Figure 6, each stars corresponds to the average grasping pressure applied during each step increment of the reference torque. The inverse "torque to grasping pressure" characteristic is shown in the bottom graph of Figure 6 (solid line).

During hand opening phase, the "pressure-to-torque" characteristics could not be evaluated through the pressure sensorized object for negative values of the torque. So the characteristic was appositely modified in its initial part, in order to drive finger extension when small EMG residual activity was detected. A force threshold was set at 10 mbar, under which a constant negative motor torque (-0.2 Nm) was applied to drive hand opening (dotted line in bottom graph of Figure 6).

3 EMG-DRIVEN ROBOTIC-ASSISTED BILATERAL TRAINING OF GRASPING

In the developed system, the grasping pressure estimation of the free hand was performed by means of a multi-channel surface EMG system and a neural-network processing algorithm. The overall control architecture of the bilateral training system for grasp, with the indication of information flow and processing among all different modules is shown in Figure 7.

In order to conduct tuning and performance evaluation of the system, two pressure sensorized objects were introduced for measuring the interaction forces between hands and grasped objects. One pressure sensorized object was used for measuring the grasping pressure of the free hand; data was then used as a reference for training a multi-layer Neural Network (NN), in charge of estimating the grasping pressure from the EMG signals (see block *Hand 1* in Fig. 7) measured at the same hand. The second identical sensorized object was used to validate performance of the EMG-driven hand exoskeleton, worn at the opposite hand (see block *Hand 2* in Fig. 7): since the system is intended to symmetrically replicate the grasping force from the free to the assisted hand, the grasping pressure measured at the two hands was expected to match, in case of a completely passive assisted hand.

3.1 EMG processing for grasp control

Forces exerted in hand grasping are correlated with the activity of the recruited muscles, so that EMG measurements can be used to guide the level of assistance during human-robot interaction ([33], [34], [35]).Several methods,

Fig. 5: The sensorized graspable object (left) and detail of the pressure sensor (right).

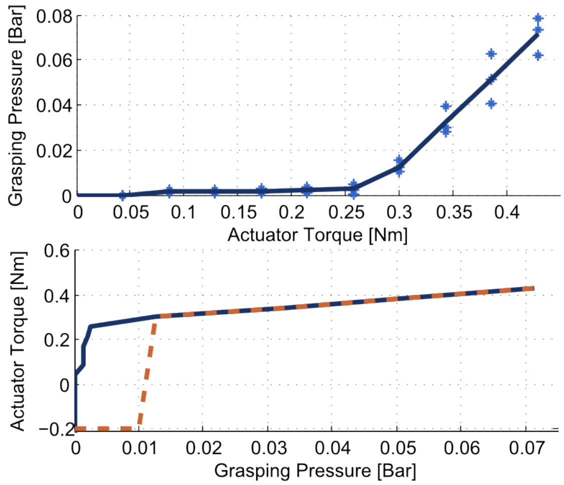


Fig. 6: The experimentally evaluated torque-to-grasping pressure characteristic (top), and the inverse characteristic (bottom) used for driving the exoskeleton.

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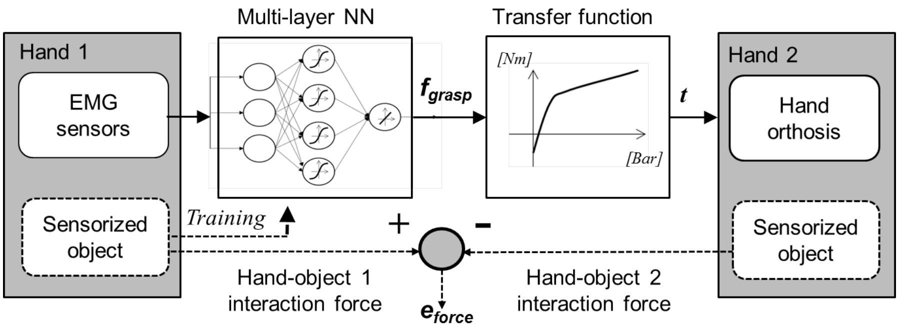

Fig. 7: Global data flow of the system. Dotted lines indicate either training or evaluation information.

such as neural networks [36], neuro-fuzzy classifiers [37], and support vector machines [38], have been successfully proposed to estimate the relationship between EMG activity and exerted force in isostatic conditions. In this study, with the aim of estimating the hand grasping force, three pairs of electrodes were placed on three main forearm muscles: the extensor digitorum longus (EDL), the flexor digitorum longus (FDL) and the abductor pollicis brevis (APB). SENIAM recommendations were followed for sen-

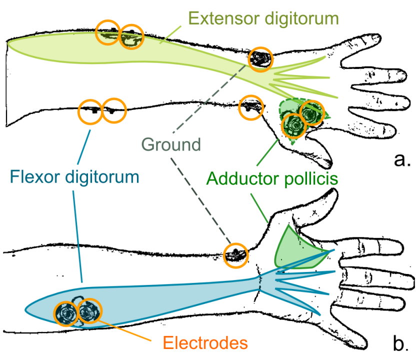

Fig. 8: The sensor location of the EMG electrodes on the left arm. Anterior surface (a.) and posterior surface (b.).

sor positioning and skin preparation. Ag/AgCl foam pre-gelled electrodes with a diameter of 24 mm were used with an inter-electrode distance of 20 mm for each bipolar derivation. Ground and the reference electrodes for all bipolar derivations were positioned at the wrist. The map of the EMG sensor locations is shown in Figure 8. All electrodes were connected to an amplifier (g.USBamp amplifier, http://www.gtec.at/) and digitally converted (512 Hz sample frequency, 12 bit resolution). Signals were digitally filtered by a band-pass filter between 20 Hz and 500 Hz. The linear envelopes of the EMG signals were obtained through full-wave rectification and low-pass filtering (1 Hz cut-off frequency). These processed EMG signals were set as input features for a multi-layer perceptron Neural Network (NN), used for estimating the grasping force from the extracted EMG features. The use of a NN allowed to overcome non-linearities and the multi-dimensional issues associated to the mapping from EMG muscle activity to the grasping force. In order to investigate the behavior of different NN architectures, a preliminary dataset was acquired from a group of six healthy subjects. Each subject wore the EMG electrodes on the left forearm and was asked to grasp a pressure sensorized object. Visual feedback of the grasping pressure was provided by means of a bar displayed on an LCD screen. Then, the subject was asked to match the level of exerted pressure with a varying reference, indicated by a red line displayed on the screen. EMG signals (input of the NN) and the measured grasping pressure (output reference of the NN) were recorded. The optimal NN architecture was selected by analyzing performance of different networks over the same dataset, differing for the number of hidden layers and number of neurons in each hidden layer. The best trade-off between performance and complexity was represented by the four-neurons single hidden layer NN. Figure 9 shows the experimental performance of the selected optimal NN in the case of multiple consequent grasping and releasing movements.

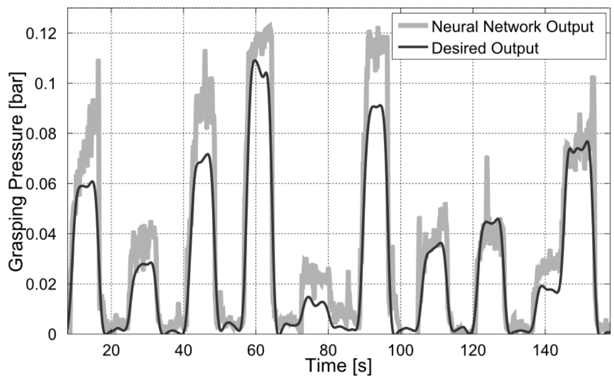

Fig. 9: Comparison between the grasping pressure estimated by the Neura Network and the measured value

4 Experimental Evaluation of Bilateral Training for Grasping

All experiments were conducted in accordance with the WMA Declaration of Helsinki and subjects provided written consent to participate. The first experiment assessed the system capability of replicating grasping force from one hand to the other. The experiment was conducted with healthy subjects and consisted in quasi-static bilateral grasping sequences, where the applied grasping pressure was compared between the two hands. The second experiment evaluated system usability in task-oriented grasping sequences, involving natural modulation of the grasping force. The experiment consisted in a bilateral grasping and

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lifting task of cylindrical objects with different weights, thus inducing modulation of the grasping force in order to avoid slippage. The third experiment investigated performance and usability of the proposed system with two stroke patients. System performance and patients' muscle activation were evaluated in a sequence of bilateral grasping tasks in three experimental conditions: with the the impaired hand passive, with active use of the impaired hand, and finally without the use of the exoskeleton for comparison purposes.

4.1 Experiment 1: Performance of the bilateral rehabilitation system

Six healthy subjects (right-handed, aged 30.2 ± 4.9, 3 females) were enrolled for the study. The right hand size of each participated was measured (distance between the wrist and middle fingertip, and circumference around the palm) and reported in Table 1. Subjects sat comfortably in front of a table, with their left and right forearms lying on the surface. Surface electrodes for EMG measurement were applied on the left forearm, with the same configuration previously described in Section 3.1. Also the EMG from the right FDL muscle was recorded for both monitoring EMG activation and ensuring complete relaxation of the assisted hand. In order to train the NN, subjects were asked to perform a preliminary training session as described in Section 3.1, using the left hand only and one pressure sensorized graspable object. After the training of the NN, subject were asked to perform bilateral grasping tasks with robotic assistance for the right hand. The BRAVO hand exoskeleton was worn on the right hand, and subjects were asked to keep their right hand completely passive.

A second pressure sensorized graspable object was introduced for the assisted hand. Similarly to the NN training session, subjects were asked to perform a sequence of grasping tasks, matching the grasping pressure exerted by the left hand with a reference value. Both the measured (white bar) and reference (red line) grasping pressures referred to the left hand, were shown on a screen as feedback (Fig. 10). The experiment was composed of a sequence of 10 grasping tasks. During each task, the grasping pressure reference was held constant for a period of 6 s, at a value randomly chosen between 10 and 60 mbar, then a relaxation period of 6 s followed. The grasping pressure estimated by the NN was replicated by the hand exoskeleton on the right hand, and measured through the right sensorized object. The grasping pressure of the robotic-assisted hand was not provided as visual feedback to the subject. The experimental setup is shown in Figure 10.

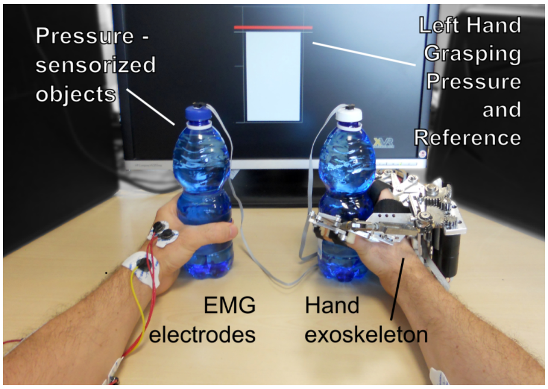

Fig. 10: Experimental set-up of Experiment 1

4.2 Experiment 2: Different weight-object lift test using EMG-based force estimation

The second experiment evaluated system performance in a bilateral task-oriented experiment, where robotic assistance was modulated for the grasping and lifting of objects with different weights. The six healthy subjects of the first experiment were enrolled for this purpose. The experimental set-up was analogous to the first experiment, except for the graspable objects. Three pairs of rigid cylindrical shaped objects, having respectively the weight of $20g$, $500g$ and $1000g$, were subsequently presented to the subject (Figure 11). For each pair of objects, subject had to simultaneously grasp them with the free and robotic-assisted hand. In order to avoid any muscle contraction at the level of the arm, the lifting phase was simulated by removing the ground support where objects were placed on. Subject were asked to hold the objects suspended, avoiding any slippage while the support plane was slowly lowered. As in the previous experiment, the right hand was passive (assured by the monitoring of the right EMG) and the grasping was completely assisted by the exoskeleton. The NN used for estimating the grasping force of the free hand was the same trained in the previous experimental session.

Each lifting phase lasted for 4 s, then the movable support was recovered at the starting position and subjects were asked to release the grasp. Subjects repeated the grasping-lifting-releasing task three times for each pair of objects, and data recorded during the last lifting repetition were considered for further analysis.

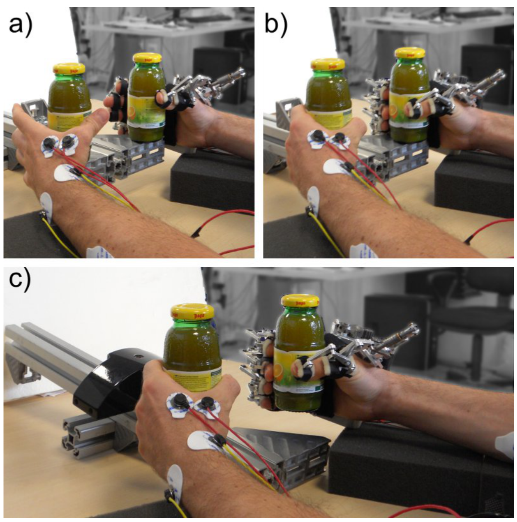

Fig. 11: Sequence of movements in Experiment 2: a) hands closing; b) grasping c) simulated lifting.

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4.3 Experiment 3: Evaluation of performance with stroke patients

The robot-assisted bilateral rehabilitation system was evaluated in a rehabilitation setting involving two male chronic stroke patients (aged 53 and 65, upper limb Fugl Meyer Assessment score of 42/66 and 36/66 respectively) with hemiparesis at the right side. The assessment was conducted at the Unit of Neurorehabilitation of the University Hospital of Pisa, Italy. The experimental set-up was analogous to the one in Experiment 1 (see Section 4.1).. The patient sat on a comfortable, height-adjustable seat, with forearms lying on a table. In front of the patient an LCD screen showed the reference and feedback bar related to the grasping pressure of the healthy hand only. The aim of the experimental rehabilitation session was to evaluate the capability of the exoskeleton to assist patient grasping. Three different experimental conditions were performed: “Passive”, in which the patient was asked to let the robot guide his impaired hand passively, “Active”, in which the patient was asked to actively cooperate with the robot to accomplish the grasping task, and “Free”, in which patient was asked to perform grasping tasks with the paretic hand, but without the exoskeleton. In both “Passive” and “Active” conditions the grasping force provided by the exoskeleton was modulated by the patient through EMG of the unimpaired hand. In order to train the NN, each patient performed a preliminary training session as described in Section 3.1, using the unimpaired hand and one sensorized graspable object. The overall time required by the training phase was less than 5 minutes.

Fig. 12: The rehabilitation session with stroke patients

Once the NN was trained, the patient was instructed to execute different sequences bilateral grasping movements. Similarly to the set-up of Experiment 1 (Section 4.1), patient was asked to grasp two identical objects matching a given pressure reference. Each experimental session consisted in a sequence of about 10 repetitions. Similarly to Experiment 1, reference and visual feedback of the grasping force exerted by the unimpaired hand was provided to patients. In the “Passive” and “Active” conditions, the grasping force of the unimpaired hand was on-line estimated and the robotic assistance was symmetrically applied to the impaired hand. The “Free” condition was performed for comparison purpose with no exoskeleton worn on the impaired hand.

5 Results

5.1 Experiment 1: Results

In Figure 13 we report a graphical representation of performance for two representative subjects only. The top line shows the comparison between the grasping pressures of the free hand and the robot-assisted hand, whereas the bottom line shows the linear regression between the grasping pressure estimated from EMG signals (NN output) and the grasping pressure of the free hand (NN reference). Results for all subjects are reported in Table 1. The mean

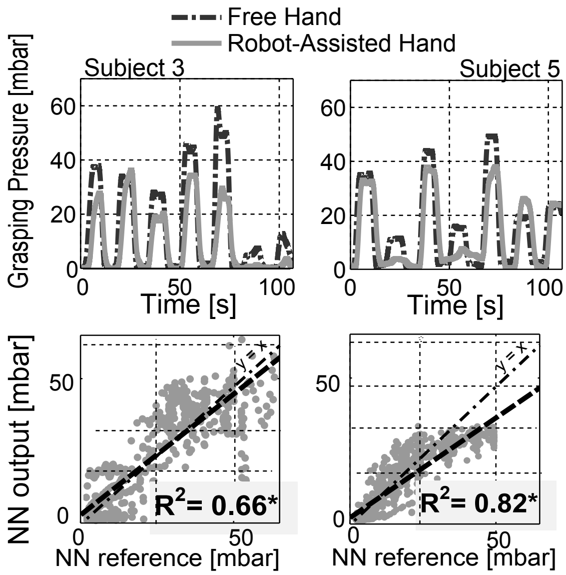

Fig. 13: Results of experiment 1 for two representative subjects, showing the grasping pressure tracking (top) and the correlation between the grasping pressure NN estimation and reference(bottom).

absolute error (MAE) refers to the difference in the grasping pressure [mbar] measured by the two sensorized objects. The coefficient of determination (R^2) refers to the correlation between the measured grasping force and the NN estimation from EMG signals. In the ideal case, a linear coefficient equal to 1, and intercept term (bias) equal to zero are expected. As regards the estimation of the grasping pressure from EMG signals, the linear regression values report an average correlation coefficient of 0.77 ± 0.10, and a bias of 3.95 ± 1.93, indicating a relatively good tracking performance.

Considering the performance of the whole system, including both the estimation and actuation of the grasping pressure by means of the hand exoskeleton, the system operation reported an average absolute error of 10.5 ± 2.9 mbar, equal to about $21 \pm 6\%$ of the explored range of pressures (average value computed in the group of 6 healthy subjects). System behavior in tracking of the grasping force can be also evaluated by top graphs in Figure 13. The graphs for two representative subjects show that tracking

Subject	Hand Size		MAE	Regression		
	ϕ [cm]	Length [cm]	[mbar]	R^2	Slope	Bias [mbar]
Sbj 1	22.5	19.5	11.83	0.92	1.1	3.1
Sbj 2	19	16	15.04	0.71	0.5	2.6
Sbj 3	20.5	18.5	9.65	0.66	0.8	3.9
Sbj 4	20	17	11.58	0.85	0.9	8.1
Sbj 5	21	19	6.82	0.82	0.7	3.1
Sbj 6	21	18	8.37	0.68	1.0	4.5
Ptn 1	21	19	4.13	0.87	0.8	1.7
Ptn 2	21.5	18.5	11.8	0.65	0.7	4.6

TABLE 1: Results for Experiment 1 (Subjects 1-6) and for the first session of Experiment 3 (Patient 1 and 2)

is good for middle values of the explored grasping force range, while tracking error is higher for very low and very high force values. For low values, errors can be introduced by static friction of the actuators gearhead, while for higher values, a saturation effect can be induced by mechanical compliance between exoskeleton links and finger phalanxes.

5.2 Experiment 2: Results

All the subjects managed to successfully perform the lifting tasks with all the object pairs. The EMG data, the estimated grasping pressure value, and the reference assisting torque component were recorded during the lifting phase.

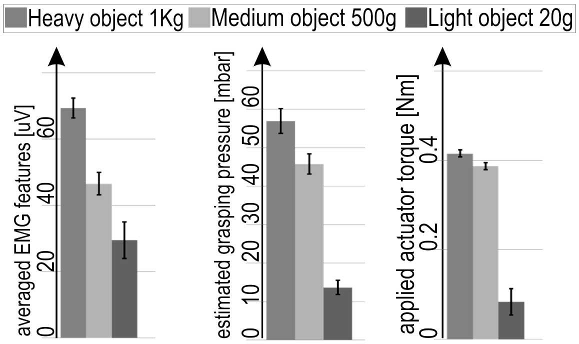

Fig. 14: Results reported in Experiment 2, averaged during the lifting of objects with different weight

The averaged data for each subject, related to the central 2s period of the lifting phase for each pair of variable-weight objects, are shown in Figure 14. From the intensities of the EMG activity it can be noted that subjects were effectively able to modulate the grasping pressure in relation to the weight of each pair of objects. This is in line with the natural execution of a grasping task, where grasping forces between fingers and the grasped object are held just above the level of static friction required to avoid slippage [39]. Considering a linear friction model, the minimum required grasping pressure should increase linearly with the weight of the object. With respect to the obtained data, it appears that the grasping pressure was over-estimated for the 500g object, moreover such non-linearity was exaggerated in the estimated actuator torque due to the non-linear calibration profile (Figure 6) of the hand exoskeleton.

5.3 Experimental rehabilitation sessions: Results

As described in Section 4.3, the two chronic stroke patients performed the rehabilitation bilateral exercise in three conditions called "Passive", "Active", "Free" respectively.

Analogously to the Experiment 1 carried out with healthy subjects, results related to the Passive condition of the experimental rehabilitation session are reported in Table 1 (Patient 1 and 2) as the linear regression coefficient R^2 between the measured and estimated grasping pressure exerted by the free hand, and the MAE between the grasping pressure exerted by the free and the robot-assisted hand. Mean value of the MAE, averaged over patients, is 7.9 $\pm$5.4 mbar, corresponding approximately to 15$\pm$11% of the explored range of pressures.

Figure 15 shows time-domain data recorded for the two patients during the "Passive", "Active" and "Free" experimental conditions. Data are related to three representative repetitions of the proposed bilateral grasping task. As expected, the NN estimation of the grasping pressure performed well for all the patients and conditions. In fact, since the grasping pressure estimation involves operation of the unimpaired hand only, system performance are similar to the experiment conducted with healthy subjects (Experiment 1).

Table 2 reports for each patient, the coefficients of determination (R^2) between muscles activities and grasping pressures time series of both the Impaired (I) and the Unimpaired (U) sides, acquired during the "Active" and "Free" conditions. The linear envelopes of the FDL EMG signals were computed before calculating the R^2 coefficients. Considering the matching of the grasping pressure between the unimpaired and the robot-assisted hand, differences arise between conditions and patients. Discussions of the obtained results are presented in the following section.

R^2 **Coefficients**		FDL U Pressure U	FDL I Pressure I	FDL I FDL U	Pressure I Pressure U
Ptn 1	Active	0.61	0.29	0.17	0.80
	Free	0.64	0.30	0.14	0.50
Ptn 2	Active	0.68	0.03	0.03	0.43
	Free	0.74	0.03	0.11	0.04

TABLE 2: Coefficients of determination (R^2) computed between FDL muscles activities and grasping pressures for the Impaired (I) and the Unimpaired (U) sides

6 DISCUSSION

In experiment 1, force tracking of grasping pressure was performed with an average error of 10.4 mbar, corresponding to about 20% of the explored range of pressures. The relatively low error obtained between grasping pressure values of the two hands assessed that the system was able to symmetrically replicate the grasping pressure with reasonable precision for the proposed rehabilitation approach. Residual errors in the tracking of the grasping pressure can be attributable to both estimation and actuation errors. In particular, estimation errors are introduced by noise and cross-talking in EMG signals, and by non-ideal modeling of muscle activation patterns through the NN. Regarding the actuation of the estimated grasping force, friction and mechanical compliance between the exoskeleton links and the hand can introduce differences in force exerted at the fingertips with respect to the hand exoskeleton calibration.

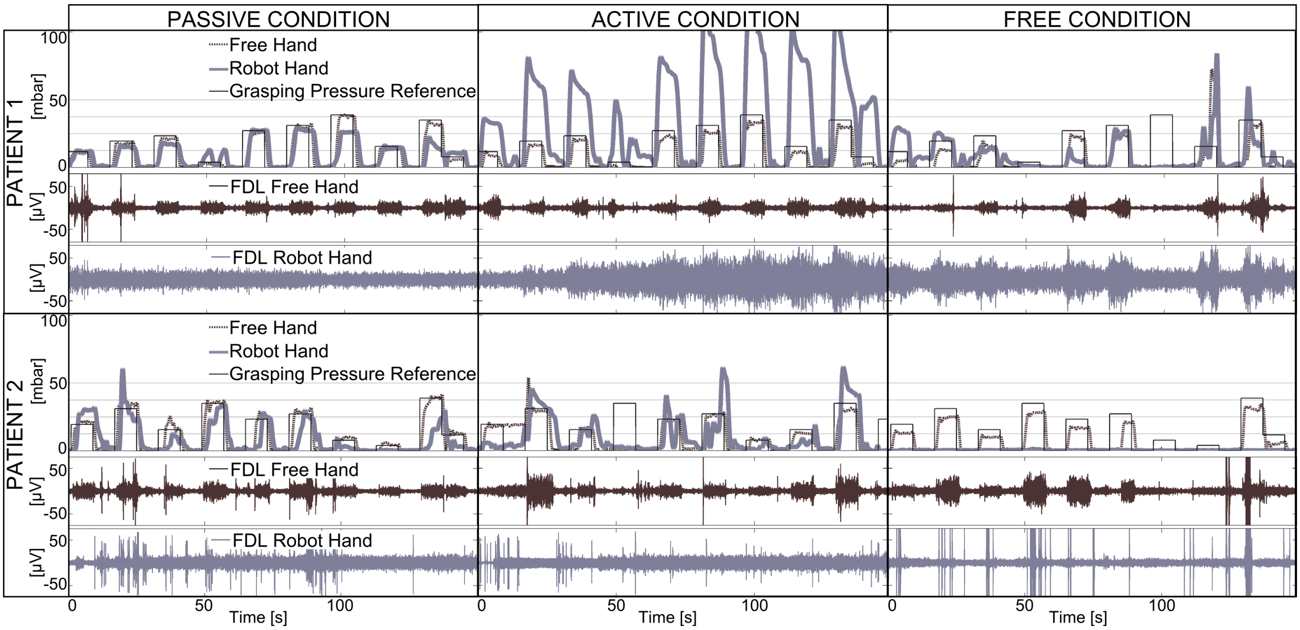

Fig. 15: Data acquired during the experimental session with stroke patients. Graphs are referred to the Active and Passive conditions (columns) and patients (rows), showing three representative bilateral grasping sequences

Experiment 2 evaluated the behaviour of the system in bilateral tasks requiring intrinsic modulation of the grasping force. The experiment was of particular interest since objects are usually grasped exerting the minimum force required to overcome slippage. Results pointed out that subjects were able to modulate the grasping force accordingly to the weight of the object, thus following the expected natural behavior [39]. Yet, results obtained for the 500 g object showed a grasping force higher than the ideal behavior suggested by a linear friction model. Such non-linearity has been probably introduced by errors in estimation of the grasping force, since averaged EMG features in the same Figure 14 show a more linear behavior. Also it has to be considered that additional errors can be introduced in general by the subject over-squeezing the object with respect to the minimum grasping force required for avoiding slippage.

Experiment 3 was conducted with two stroke patients, with different level of hand impairment. Both patients were able to perform the proposed exercises with robotic assistance, moreover, they verbally reported a pleasant feeling associated to the opening of the paretic hand. From the analysis of force profiles reported in Figure 15, some relevant observations can be drawn. Taking into account the different level of impairment and motor outcomes of the two patients (hypertonia for Patient 1, flaccidity for Patient 2), results will be discussed separately.

Patient 1. The "Free" experimental condition, performed without robotic assistance, provided useful information about residual motor capabilities of each patient. Patient 1 exerted noticeable grasping force with the impaired hand, though with coarse modulation. In several grasping repetitions the applied grasping pressure was exceeding or insufficient with respect to the given reference. Such behavior can be explained in terms of of abnormal muscle activation induced by spasticity, and in termes of reduced touch sensitivity at palm of the impaired hand, since no visual feedback of grasping pressure of the paretic hand was provided. Patient 1 showed abnormally high EMG activation throughout the experiment. By comparing EMG amplitude between hands, it emerges a relevant spasticity of the impaired hand, with the subject unable to relax muscles during rest periods. High EMG activity measured in proximity of the FDL muscle might also be induced by cross-talking of other muscles involuntary contracted during the grasping task. Additionally, when Patient 1 grasped the object in the "Free" condition, he was unable to keep the arm relaxed with proper supination of the forearm: in order to apply grasping force to the object, he tended to move the forearm toward the body, as by abnormal flexion synergy in stroke.

In the "Passive" experimental condition, Patient 1 accomplished grasping repetitions with overall good performance in modulation of the grasping force. The average error (MAE) shown in Table 1 was similar to values reported by healthy participants. By observing top graph in time domain of Figure 15, a good matching of the grasping pressure between hands can be noticed, except for few repetitions showing lower pressure for the robotic assisted hand, probably due to mechanical compliance between fingers and the exoskeleton. Timing for grasping and releasing of the objects were also accurately followed with respect to the given reference. EMG amplitude of the impaired hand remained moderately and uniformly high in the whole experimental session. Such muscle activation was due to residual spasticity, since corresponded to no overt force exerted by the hand.

In the "Active" condition of Patient 1, the addition of grasping force applied directly by the impaired hand was evident (Figure 15) and resulted into an overall grasping pressure exceeding the prescribed reference. This can be explained both by the fact the system did not compensate for residual forces exerted by the impaired hand, and by a combination of muscle co-contraction and reduced sensitivity at palm of paretic hand.

In relation with the "Active" condition, back-drivability and transparency of the robotic device are important factors to be considered. The implemented hand-exoskeleton is back-drivable, but not transparent due to the actuators gear reduction. However, while transparency plays a relevant role in dynamic movements, in the proposed scenario it becomes less influential: due to the quasi-static grasping conditions, the exoskeleton and the hand can be considered to work in parallel as regards the overall grasping force applied to the object. As evidenced by results obtained for the "Active" condition, the measured grasping pressure is modulated both by the exoskeleton and by the hand.

The observed pattern of EMG activation was comparable to the given grasping pressure reference, suggesting that patient voluntary applied grasping forces with the impaired hand, though with limited control and sensitivity. Conversely, muscle relaxation appeared hindered, similarly to what observed in the "Free" condition.

Patient 2. Outcomes of the "Free" experimental condition of Patient 2 presented negligible grasping pressure at the impaired hand. Measured EMG showed a constant, uniform amplitude due to a low residual spasticity, with no modulation with respect to the reference grasping pressure. Peaks evidenced in the EMG signal of the impaired hand were due to the occurrence of myoclonus, as an outcome of stroke; peaks occurred with higher frequency during grasping tasks than in the releasing and rest phases. EMG amplitude at the healthy hand was lower with respect to Patient 1, this led to a diminished performance of the NN in estimating the grasping force (Table 1). In the "Passive" condition, Patient 2 was able to modulate the grasping force with good accuracy (Table 1), comparable with values achieved by healthy subjects. Robotic assistance appeared to apply slightly higher grasping pressure than reference in the first phase of the experimental session, conversely lower grasping pressure than reference in the final phase. Such behavior could be caused by a progressive variability, due to mechanical compliance, of contact points between fingers and links of the exoskeleton. Myoclonic patterns can be noted also in the EMG signal of the "Passive" condition. Regarding the "Active" condition, since Patient 2 was not able to exert noticeable grasping force with the impaired hand ("Free" condition), performances similar to the "Passive" condition were expected. Experimental results showed modulation of the grasping force comparable to the "Passive" condition, yet with lower performance. Discontinuity of the robotic assistance was noticeable in some of the grasping repetitions. Considering muscle activation measured at the unimpaired hand, such behavior might be caused by a lower signal to noise ratio in EMG signals, producing a less stable estimation of the grasping force.

Results reported in Table 2 summarize correlations between muscles activities and grasping pressures measured during the "Active" and "Free" conditions. As expected, correlation between muscle activity and grasping pressure was higher for the unimpaired side (first column in Table 2) than the impaired side (second column in Table 2). Moreover, left and right FDL muscles activities showed low correlation (third column Table 2) evidencing anomalies in muscle recruitment of the impaired side. As regards the correlation between left and right grasping pressures, R^2 was higher in the "Active" condition for both patients (fourth column Table 2). It confirmed that the exoskeleton effectively assisted patients in accomplishing the grasping task, improving congruence between sensory feedback and motor intention. Such congruence is the key factor expected to improve motor outcomes and muscles recruitment in the long term rehabilitation. Noticeably, the use of the exoskeleton did not hinder the residual motor functions of Patient 1 (Patient 2 did not have residual motor functions). Another important point to underline is that through robotic assistance, patient is allowed to perform the rehabilitation exercise, whereas without assistance he/her could be completely unable even to initiate the movement (i.e., Patient 2). Although supported by the exoskeleton, the capability to initiate and execute the motor task is expected to motivate the patient in performing rehabilitation exercises, thus encouraging progressive recruitment of the impaired hand. To this purpose, a further interesting development of the proposed approach should include adaptive modulation of the robotic assistance, compensating the increasing activation of the impaired hand. Such approach would fulfill the assistance-as-needed paradigm, ideally providing proper robotic assistance from the completely passive limb to the fully recovered motor functions.

7 Conclusions

This paper demonstrated the feasibility of a novel system for robotic assisted bilateral training of the hand. The proposed system allowed patients to perform grasping tasks of real objects with modulated robotic assistance.

Performance of the system in replicating modulated grasping force from the free to the robotic assisted hand was validated through experiments with six healthy subjects in different experimental conditions. The system could replicate grasping pressure on a cylindrical object with reasonable accuracy and relative low variability between subjects (mean absolute error of 20±7% of the explored range of grasping pressures). Moreover, subjects were able to modulate robotic assistance in a task-oriented grasping and lifting task, showing modulation strategy comparable to the expected natural behavior. Positive results were obtained also in the evaluation conducted with two chronic stroke patients. Both patients were able to accomplish the proposed tasks with precise grasp and release timing. Moreover, obtained accuracy in modulation of the grasping force was comparable to healthy subjects.

The study in stroke confirmed the advantage of driving robotic assistance by the healthy hand in bilateral training, whereas muscle activity of the impaired limb resulted unreliable, due to spasticity or flaccidity. Performance evaluation with and without the assistance of the exoskeleton evidenced that, by using the proposed system, patients were allowed to voluntary accomplish the proposed motor task receiving congruent sensory feedback. Congruence between sensory feedback and motor intention is the key factor expected to improve motor outcomes. Considering also that bilateral training has been assessed to be effective for neurorehabiltation [27], we suppose that the proposed system might be effectively introduced in rehabilitation practice. In order to evaluate the effectiveness of the system as a rehabilitation tool, future works will include a controlled clinical validation of the system through an extended period of training.

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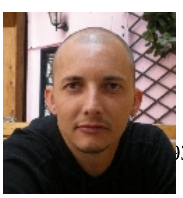

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