Wrist Rehabilitation in Chronic Stroke Patients by Means of Adaptive, Progressive Robot-Aided Therapy

V. Squeri, L. Masia, P. Giannoni, G. Sandini, and P. Morasso

***Abstract*—Despite distal arm impairment after brain injury is an extremely disabling consequence of neurological damage, most studies on robotic therapy are mainly focused on recovery of proximal upper limb motor functions, routing the major efforts in rehabilitation to shoulder and elbow joints. In the present study we developed a novel therapeutic protocol aimed at restoring wrist functionality in chronic stroke patients. A haptic three DoFs (degrees of freedom) robot has been used to quantify motor impairment and assist wrist and forearm articular movements: flexion/extension (FE), abduction/adduction (AA), pronation/supination (PS). This preliminary study involved nine stroke patients, from a mild to severe level of impairment. Therapy consisted in ten 1-hour sessions over a period of five weeks. The novelty of the approach was the adaptive control scheme which trained wrist movements with slow oscillatory patterns of small amplitude and progressively increasing bias, in order to maximize the recovery of the active range of motion. The primary outcome was a change in the active RoM (range of motion) for each DoF and a change of motor function, as measured by the Fugl-Meyer assessment of arm physical performance after stroke (FMA). The secondary outcome was the score on the Wolf Motor Function Test (WOLF). The FMA score reported a significant improvement (average of 9.33 ± 1.89 points), revealing a reduction of the upper extremity motor impairment over the sessions; moreover, a detailed component analysis of the score hinted at some degree of motor recovery transfer from the distal, trained parts of the arm to the proximal untrained parts. WOLF showed an improvement of 8.31 ± 2.77 points, highlighting an increase in functional capability for the whole arm. The active RoM displayed a remarkable improvement. Moreover, a three-months follow up assessment reported long lasting benefits in both distal and proximal arm functionalities. The experimental results of this preliminary clinical study provide enough empirical evidence for introducing the novel progressive, adaptive, gentle robotic assistance of wrist movements in the clinical practice, consolidating the evaluation of its efficacy by means of a controlled clinical trial.**

***Index Terms*—Robot therapy, stroke, wrist rehabilitation.**

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V. Squeri, L. Masia, G. Sandini, and P. Morasso are with the Department of Robotics, Brain and Cognitive Sciences, Istituto Italiano di Tecnologia, 16163 Genova, Italy (e-mail: valentine.squeri@iit.it; lorenzo.masia@iit.it; giulio.sandini@iit.it; pietro.morasso@iit.it).

L. Masia was with the Department of Robotics, Brain and Cognitive Sciences, Istituto Italiano di Tecnologia, 16163 Genova, Italy. He is now with the School of Mechanical and Aerospace Engineering, Nanyang Technological University, 639798 Singapore.

P. Giannoni is with ART Rehabilitation and Educational Centre, 161290 Genova, Italy (e-mail: psichegiannoni@alice.it).

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I. Introduction

THE complex structure of the human wrist provides the possibility to adapt hand orientation according to the required task and also enables the hand to be firmly locked while interacting with the external environment, in such a way as to transfer forces generated by the powerful forearm muscles [1] for grasping objects or tools. Furthermore, different wrist positions facilitate or hinder some finger motion, e.g., finger flexion is difficult if the wrist is in flexion. Generally, movement occurs around two main axes and combination of single rotations: flexion/extension and abduction/adduction (also known as radio-ulnar deviation). Rotation around the forearm axis is not actively possible, but is achieved by prono/supination of the radio-ulnar complex, with some shoulder contribution in specific arm postures [2].

Although the wrist is truly a mechanical marvel when it is intact and functioning, orthopedic or neurological impairments inevitably cause substantial dysfunctions of the hand motion and consequently of the entire upper extremity [1]. For this reason, rehabilitation research has focused on understanding how to restore wrist/hand motor function after stroke.

Several studies over the years have demonstrated that training procedures emphasizing intense, active and repetitive movements are of high value in promoting functional recovery. These protocols increase strength, accuracy and functional use, when applied to stroke survivors affected by hemiparesis of the upper limb [3]–[5]. Different techniques have been developed in order to integrate and boost the action of human-delivered physical therapy, with particular emphasis on robotic technology. Another promising rehabilitation technique is based on functional electrical stimulation (FES). The technique has evolved from the early studies of the 1960s [6] to the recent advances, named functional electrical therapy (FET) [7], [8]. In the future, an integration of robotic and electrical techniques could be developed, as suggested by some preliminary studies [9].

The literature on robotic wrist rehabilitation is still rather limited if compared to the proximal part of the upper limb (shoulder and elbow); moreover, the amount of effort in developing wrist rehabilitation devices by the community of mechatronic researchers as well as the engineering development level achieved so far is still rather limited [10]–[18].

One of the traditional techniques for wrist therapy is based on splints in order to reduce spasticity, prevent contracture, and improve activity after long immobilization; however, a recent review [19] shows that wearing a splint for the whole night in several consecutive days is not effective in reducing spasticity or preventing contracture but, contrarily, may have negative side effects. The main reason is that prolonged splinting tends to reduce wrist mobility inducing disuse and consequent muscular atrophy. Moreover, splint techniques are essentially *passive* and unable to recruit *neural plasticity* [20] as well as stimulate sensorimotor learning via voluntary motor control and repetitive training.

Dynamic splint techniques use additional components (springs, wires, rubber bands) to mobilize contracted joints [21] in order to provide a controlled gentle force to the soft tissue over long periods of time, thus facilitating tissue remodeling without tearing. However, both dynamic and static progressive splinting techniques must face technically difficult problems, like determining the amount of force to be delivered at the joints, while preventing further injury to articulation and stimulating voluntary motion. The problem can be overcome if dynamic splinting is delivered using devices able to modulate online the interaction and widen the range of motion. Therefore, the proposed robotic therapy protocol for wrist rehabilitation can be considered as a continuous dynamic splinting of each single DoF with the purpose to promote and stimulate the voluntary component of movement.

The robotic protocol helps subjects in completing the movements with a minimum amount of force (assist as needed principle or minimal assistance strategy) that has been demonstrated to be effective for rehabilitation cycles targeting shoulder and elbow training [22]–[26]. Because the motor system tends to behave as a "greedy" optimizer which decreases the voluntary control of movement (and therefore muscle activation) if passive motion is predominant [27], in our previous studies we used an adaptive assistance strategy: the amplitude of the assistive force field was decreased as the subject's performance indicators increased [23]–[25], [28]. In this paper, we explore an alternative adaptation mechanism: the task difficulty is increased as a subject succeeds in completing an experimental block.

Another important feature of robot therapy is that exercises should be tailored to the specific impairment of the subject [29]: with the initial measurement of the range of motion that subjects can freely reach, each session was indeed adapted to individual impairments and progressively modified over the course of the entire protocol.

As regards the underlying neurophysiological/neurological aspects, there are some indications of a possible generalization effect from distal arm training (i.e., hand and wrist) to proximal arm function (i.e., elbow and shoulder), leading to improved control of the entire arm [13], [17], [18], [30]. It is too early to draw firm conclusions and further studies are definitely necessary. On the other hand, there is a quite promising finding by Butefisch *et al.* [3]: repetitive, dorsiflexion movements of the affected wrist in stroke patients not only increase the degree of efficiency of biomechanical parameters (grip strength, isometric extension force, and rapidity of isotonic wrist extension), but also improve the upper extremity's overall motor function, as assessed with the arm section of the Rivermead Motor Assessment (RMA).

The present work aims to provide a further contribution in this direction, by assessing clinical effects of a new robotic therapy approach targeting the distal part of the arm. The proposed robotic therapy trains the three distal degrees of freedom (DoF) separately by means of three different protocols, each one designed in order to match specific needs of single articular rotations: flexion/extension (FE), abduction/adduction (or radio-ulnar deviation, AA), and forearm pronation/supination (PS).

In agreement with general principles of motor learning, the content of robot therapy was designed in order to exhibit the following features: 1) increasing task difficulty (*progressive* exercise), based on subject's performance (the exercise adapts to patient's initial skills and their improvements, if any); 2) *intense*, *active, repetitive* movements; 3) *sensorimotor integration*, given the key influence that sensory events have on motor learning in the normal and post-stroke states; and 4) *high attentional valence* and complexity of the experience, given their effects in normal subjects and neurologically impaired subjects, obtained by a friendly graphical user interface. In addition to the general principles mentioned, which apply equally well to robot therapy of proximal and distal DoFs of the paretic arm, the therapy of distal DoFs must take into account that in most patients they are mainly characterized by a very reduced and strongly biased range of motion (RoM). For this reason, we chose oscillatory movements of small amplitude and low frequency as basic modules of the robot assistance protocol, with a bias angle of the assisted oscillations that was shifted smoothly and adaptively from easier to more difficult angular positions of the joints. The working hypothesis was that this technique of robot-patient interaction might be beneficial for increasing in a substantial way the RoM of the impaired distal joints, without inducing increased spasticity.

We designed an adaptive robotic protocol for treatment of impaired wrist movements able to progressively enhance and challenge the restoration of voluntary motion and evaluated its feasibility in a preliminary pilot study, with a limited number of chronic stroke survivors and without a control group. The results show that the impaired subjects could benefit from the treatment with a measurable transfer of the improvements from the distal to the proximal DoFs of the arm.

II. Methods

A. Subjects

Nine chronic stroke subjects (seven females and two males; age = 29–72 years; Table I) volunteered to participate to this preliminary study.

A neurologist and two physical therapists selected the patients according to the following inclusion criteria: 1) diagnosis of a single, unilateral stroke verified by brain imaging; 2) sufficient cognitive and language abilities to understand and follow instructions; 3) chronic condition (at least 1 year after stroke); and 4) stable clinical conditions for at least one month before being enrolled in the robot therapy program. Table I summarizes anagraphical and clinical data: etiology, disease duration, affected side, Fugl-Meyer (FMA), Wolf Function Motor Test

TABLE I
CLINICAL DATA OF SUBJECTS. **SUBJ**: SUBJECT NUMBER; **GENDER**: MALE (M) OR FEMALE (F); **AGE** IN YEARS; PARETIC **SIDE**: RIGHT (R) OR LEFT (L); TIME SINCE **ONSET** IN YEARS; **FMA**: FUGL-MEYER ARM SECTION, 0–66 POINTS; **WOLF**: WOLF FUNCTION MOTOR TEST, 0–85 POINTS; **MAS**: MODIFIED ASHWORTH SCALE, 0–4 POINTS

Subj	Gender	Age	Side	Onset	FMA	WOLF	MAS
S1	F	63	L	4	21	35	1+
S2	M	72	L	4	33	57	1+
S3	F	49	L	8	8	27	3
S4	F	60	L	4	34	36	1
S5	M	66	L	4	11	26	1
S6	F	29	L	3	21	38	1+
S7	F	38	L	6	11	18	2
S8	F	38	R	6	27	35	1+
S9	F	57	R	3	23	42	1+

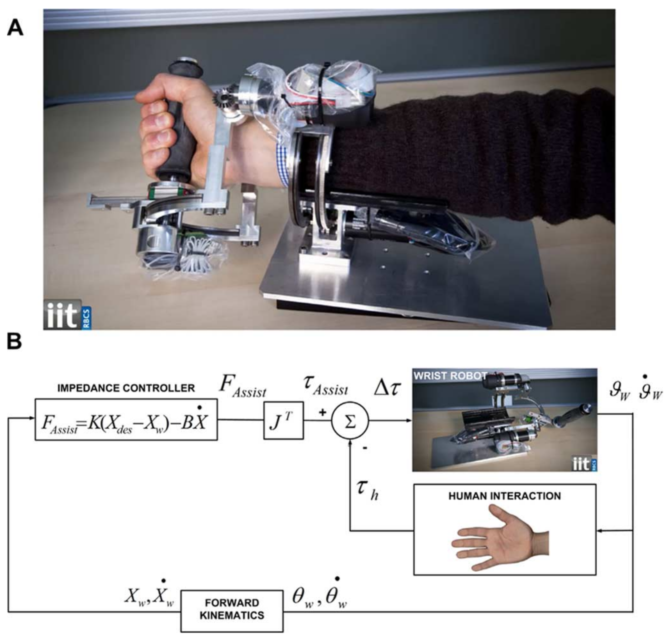

Fig. 1. Experimental setup: impedance controller for the *wrist robot*, where ϑ_w, $\dot{\vartheta}_w$ are the current joint position and velocities, x_w, $\dot{x}_w$ are the current task-space position and velocities of the end effector, F_{Assist} is the assistive force evaluated by the controller, J is the Jacobian of the *wrist robot*, x_{des} is the desired joint torques and τ_h is the human-induced joint torque.

(WOLF) and the Modified Ashworth scores (MAS). The patients were all chronic and were not involved in other rehabilitation protocols at least in the six months before the beginning of the study. This preliminary clinical study did not include a control group and thus is not a randomized, controlled clinical trial. However, the functional assessment was blinded. The research conforms to the ethical standards laid down in the 1964 Declaration of Helsinki, which protects research subjects and was approved by the ethics committee of the municipal health authority. Each subject signed a consent form conforming to these guidelines. The robot training sessions were carried out at the Motor Learning and Rehabilitation Lab of the Istituto Italiano di Tecnologia, Genoa, Italy, under the supervision of experienced clinical personnel and engineers.

B. Experimental Setup

The experimental setup (Fig. 1) consisted of a three degrees of freedoms (DoF) wrist robotic exoskeleton, a redesigned and improved version of the prototype described in [15]. The mechanical structure of the robot allows the independent activation of three movements (FE, AA and PS), with a range of rotations (FE: ±70 deg; AA: ±40 deg; PS: ±57 deg) approximately matching the physiological range of motion (FE: +73 deg↔ −71 deg; AA: +33 deg↔ −19 deg; PS: +86 deg↔ −71 deg) [31]. The robot is powered by four brushless dc motors: two motors for AA allowing gravity compensation and one motor for each of the two remaining DoFs. Impedance control scheme is used to generate an assistive force field based on relative positions of the target and the end effector (see Section II-D), with a 1-kHz sampling frequency for haptic rendering.

Subjects sat on a chair, with their torso restrained by means of suitable holders; a rigid cast was attached to the impaired arm in order to maintain the angle of the elbow joint at about 90 degrees. They were asked to grasp a handle connected to the robot end-effector and their forearm was constrained by straps to a rigid holder in such a way that the biomechanical rotation axes were as close as possible to the robot ones. In general, care was taken for avoiding compensatory movements of the body and maintaining the same posture throughout the sequence of exercises without affecting the comfort of the subjects.

C. Experimental Protocol

The main purpose of the training protocol was to promote improvements of the active range of motion for each DoF. For this reason, the assistance strategy was *progressive* and *adaptive* in the sense that the subjects were assisted in performing tracking movements of a slowly oscillating target. The target oscillations had small amplitude and the angular bias was progressively shifted from easier to more difficult wrist joint configurations over the workspace, until the subjects became unable to achieve the minimal performance requirements, based on an upper level of robotic assistive force at the specific joint. Therefore, assistance was adapted to the residual capacities of motion and the protocol avoided forcing patients with overassistance which would end up in purely passive movements. The protocol was also designed with the goal of finding a tradeoff between two conflicting requirements: 1) to maximize attention and 2) to avoid "attentional burden". For this reason, we spent effort towards the implementation of a pleasant graphics, different for the three DoFs.

The training schedule was two sessions per week, for a total of ten sessions. Each session lasted about one hour and was divided in two phases, the *test phase* (two modules) and the *training phase* [three modules, Fig. 2(A)]. Each module had a fixed duration of 15 minutes and could include a variable number of blocks depending on the subject's performance.

In the *test phase*, which occurred at the beginning (PRE module) and at the end (POST module) of each session, the robot did not provide any assistance but it was used to estimate the angular range of motion (RoM) of wrist joints: for each DoF, the subjects were asked to actively move it back and forth several times, attempting to achieve the maximum excursion. The RoM was then evaluated as the difference between peak flexion and peak extension (for the FE joint), peak abduction and peak adduction (for the AA joint), peak pronation and peak supination (for the PS joint). Moreover, the peak values

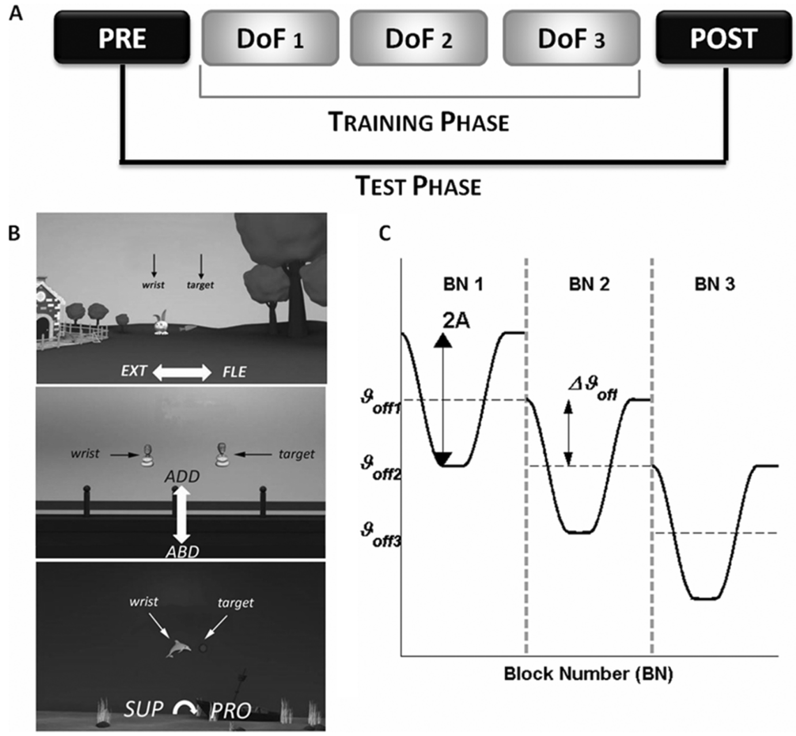

Fig. 2. (A) Scheme of the training sessions. Each session consists of two test modules (one at the beginning and one at the end of the session) and three training modules, in which one DoF is assisted by the robot and the other two inactive DoFs are constrained in the anatomical neutral position by means of mechanical holders. The order of training of the three DoFs is randomized. (B) Visual rendering, specific for each DoF. Against a DoF-specific background, subjects receive in real time the visual feedback on the motion of the target and the active DoF, respectively. (C) Harmonic-clipped motion of the target. The five oscillations of the first block occur around an angular offset ($\theta_{\mathrm{off}1}$), evaluated in the initial part of the test phase. The second block is activated if and when the first one is successfully terminated, with an offset angle which is shifted by an amount equal to the oscillation amplitude. During a given block, the five oscillations are "clipped" in the sense that at the end of each semi-oscillation the target is stopped if the tracking error exceeds a threshold. There is a deadline for the subject to re-enter a window of tolerance: if it is not met, the current training module is aborted and the next one is initiated.

of flexion, abduction and supination, respectively, were used by the robot controller during the training phase as an initial starting position $\vartheta_{\mathrm{off}1}$ for the training algorithm.

The *training phase* was structured in three separate modules, (FE, AA, and PS) and the assigned task consisted of tracking a harmonically moving target, with a specific visual rendering implemented for each DoF [Fig. 2(B)].

1) For the FE movements a "rabbit" (associated to the wrist angle) was supposed to track a "carrot" (associated to the target angle), both moving back and forth, along a horizontal path on the screen over a number of trials.
2) For the AA movements both the wrist angle and the target were represented as "monks" levitating, up and down, vertically on the screen.
3) For the PS movements a "dolphin" (the wrist angle) chased a "ball" (the target) along a circular path, like jumping back and forth against a watery environment.

For each module, the inactive DoFs were held in the neutral anatomical position by means of mechanical clutches.

During a given block of trials, the harmonic motion of the target (either the carrot, the monk, or the ball) is described by the following equation:

$$\vartheta_T(t) = \vartheta_{\mathrm{off\_BN}} + A \cdot \cos(2\pi\, t/T) \tag{1}$$

where $\vartheta_{\mathrm{off\_BN}}$ is the angular offset used in the Nth Block (BN stands for Block Number), T is the oscillation period, and A is its amplitude; at each time instant, θ_T is compared with the angular position θ of the exercised DoF. We used slow oscillations of small amplitude of the targets, in order to increase progressively the achieved RoM: $\mathrm{T} = 4$ s and $\mathrm{A} = 5$ deg. During a trial, the target motion was broken into two "clipped" semi-oscillations, while the robot provided an adaptive assistive torque. After one semi-oscillation the target was stopped if the tracking error (the absolute value of $\theta_T - \theta$) exceeded a threshold of 2 deg waiting for the subject's assisted motion to re-enter the threshold above, with a deadline of 4 s. If the deadline was not met the trial was considered unsuccessful. Successful trials were rewarded with a pleasant acoustic signal, allowing subjects to online follow their progress. If the five trials of a block were successfully completed, the block counter BN was increased by one and the angular offset $\vartheta_{\mathrm{off\_BN}}$ was increased by $\Delta\vartheta_{\mathrm{off}} = A = 5$ deg, thus initiating the next block [Fig. 2(C)]. Summing up, the duration of each trial (complete target oscillation) can range between 4 and 8 s, with a total duration of a block between 20 and 40 s, and the angular offset of each block is characterized by $\vartheta_{\mathrm{off\_BN}}$ in the following equation:

$$\vartheta_{\mathrm{off\_BN}} = \vartheta_{\mathrm{off}1} + (\mathrm{BN} - 1)\Delta\vartheta_{\mathrm{off}} \tag{2}$$

where $\vartheta_{\mathrm{off}1}$ is the initial angular bias, evaluated in the first module of the *test phase*, as mentioned previously.

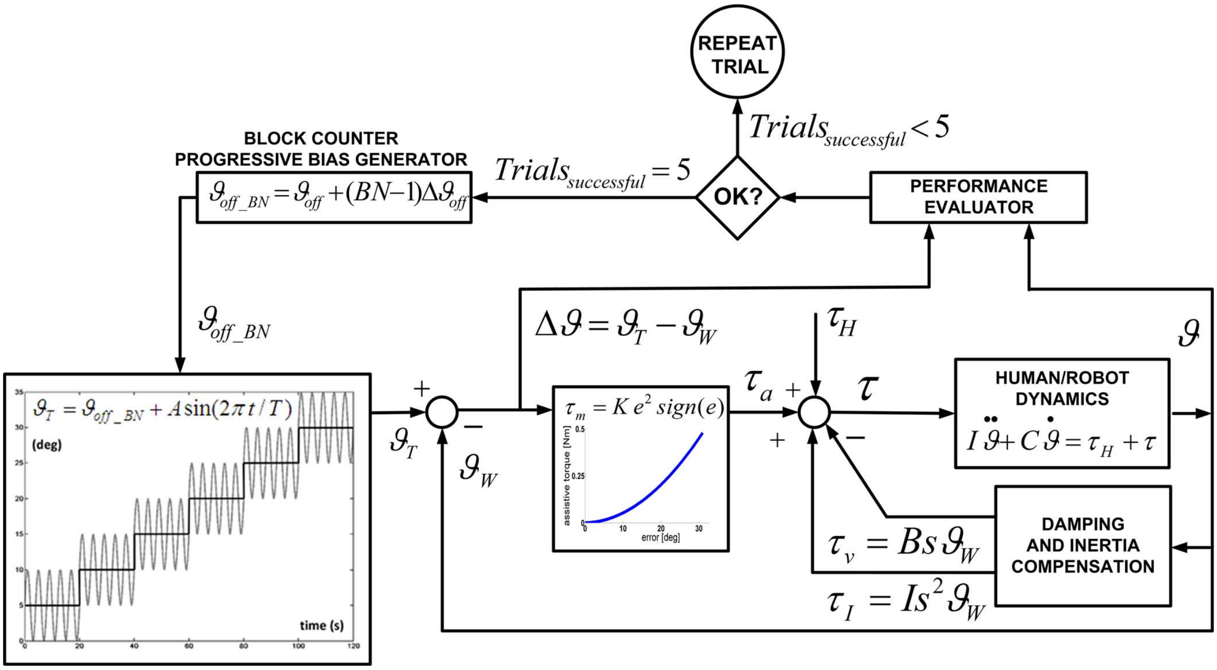

Fig. 3. Controller diagram, which applies to each of the three angles (AA, FE, PS) in the training module. An "assist-as-needed" torque τ_A quadratic term supports the tracking task by continuously delivering assistive torque to the subject's wrist τ_W in presence of angular mismatch $\Delta\vartheta$ between the target ϑ_T and the actual wrist angles ϑ_W; assistance is complemented by a damping τ_v and an inertia τ_I compensation terms. The performance evaluator block checks if the trial is successful and every five right oscillations ($\mathrm{Trials}_{\mathrm{successful}} = 5$), the block number *BN* is increased by 1 and the offset of the target motion ($\vartheta_{\mathrm{off\_BL}}$) is increased by an amount equal to the amplitude of the target oscillation $\Delta\vartheta_{\mathrm{off}}$ (5 degrees) spacing a further portion of the joint ROM. Contrarily, if the subject cannot reach the requested performance ($\mathrm{Trials}_{\mathrm{successful}} < 5$), the training module continued until the maximum allowed training time (15 min).

In the first block of trials the angular offset is equal to θ_{off1} and it corresponds to the lowest angular excursion a subject can reach voluntarily for each of his/her wrist joint.

The number of blocks a subject is able to complete is supposed to increase if the training procedure is effective in inducing motor improvements in terms of the effective range of motion. Therefore, we introduced an indicator of improvement, related to the robot assistance protocol: Range of Assisted Motion (RoAM). This indicator, which expresses the maximum angular joint excursion the subjects succeeded in reaching by the support of the robotic assistance, is defined as follows for each exercised DoF:

$$\mathrm{RoAM} = (\mathrm{BN} + 1)\mathrm{A}. \tag{3}$$

Such an indicator is obviously a multiple of 5 degrees and usually is higher than the active RoM due to the influence of robot assistance, which helps subjects to move the joint in the last part of the exercise when the subjects are not able anymore to voluntarily complete the tracking task.

Each module had a fixed duration of 15 minutes and could include a variable number of blocks depending on subject's performance.

In summary, the implemented training procedure is progressive and adaptive, using small and slow oscillations with an initial angular offset that progressively shifts from easier to more difficult joint positions: the neutral position of stroke subjects is usually altered by hypertonia and muscular atrophy due to inactivity, resulting in a wrist configuration in flexion rather than extension, abduction rather than adduction, and supination rather than pronation. Robot assistance helps the patients to move away from the natural, pathological posture thus increasing the RoM of the different DoFs.

D. Robot Assistance Control Scheme

The haptic interaction between the robot and the patients is implemented, for each DoF, by a combination of different torques, according to the scheme illustrated in Fig. 3.

1) An assistive torque component helping the subject to carry out the tracking task. It is characterized by a nonlinear elastic force with a parabolic profile, which attracts the end-effector to the moving target proportionally to the square of the angular distance between the end-effector and the target, with a gain $\mathrm{K} = 3$ Nm/rad^2

$$\tau_A = K|\vartheta_T - \vartheta|^2 \,\mathrm{sign}(\vartheta_T - \vartheta). \tag{4}$$

The choice of the parabolic profile is suggested by the need to achieve a smoother change in the assistive torque when the direction of motion is inverted due to the oscillatory patterns of the target.

2) A damping component generating a viscous torque was also provided in order to introduce a stabilizing effect in the human–robot haptic interaction, preventing nonfunctional oscillations

$$\tau_V = B\,\dot{\vartheta}. \tag{5}$$

The value of the viscous coefficient B was set to a value (0.001 Nms/rad), experimentally chosen after pilot trials.

3) An inertial torque component (only for the PS DoF) intended to partially compensate the moment of inertia of the wrist exoskeleton, thus improving the backdriveability of the device

$$\tau_I = I\,\ddot{\vartheta}. \tag{6}$$

The value of the gain used in the inertia compensation ($\mathrm{I} = 0.001\ \mathrm{Nms}^2$) is a fraction of the combined inertia of the human wrist and the robot.

The blocks of the assistive control scheme (Fig. 3) include an Oscillatory Target Generator, characterized by (1), a Progressive offset Bias Generator, using (2), and the Performance Evaluation Module, which tests the subject capability to complete successfully the five prescribed tracking oscillations in the current block. If the test is passed, the Bias Generator moves up one step, if it is not, the trial is aborted.

E. Treatment Protocol

As previously specified, the training schedule included two 1-hour sessions per week. In order to avoid systematic effects on measured performance due to muscle fatigue, the order of training of the three DoFs during a session was randomized. More precisely, three different exercising sequences were defined: sequence A (FE, AA, PS); sequence B (AA, PS, FE); sequence C (PS, FE, AA). During the first session all subjects were trained starting with sequence A, whereas in the remaining sessions each participant was treated by randomly selecting one of the sequences A, B and C. In this way every physiological movement was alternately trained as first, second and third in the sequence.

III. Data Analysis

A. Robotic Outcomes

The measures of the voluntary range of motion (RoM) collected in the test phases of each single session and the range of robotic assisted motion collected during the training phases (RoAM) were analyzed. In order to compare the results of the analysis coming from the three DoFs, which are characterized by different distributions, we normalized the data by computing the ratio between the measured parameters (RoM and RoAM) and the maximum motion allowed by the device for the given DoF: 130° for FE, 54° for AA and 115° for PS.

We estimate the jerk (Teulings' index) as the root mean square of the jerk (third time derivative of the trajectory), normalized with respect to movement amplitude and duration [32]. This indicator is a unit-free measure.

B. Clinical Outcomes

Subjects' performance was assessed three times during the study: before starting the protocol (T0), at its completion (T1), and 12 weeks post-treatment (T2-follow up). We used the Fugl-Meyer motor assessment for the upper extremity (FMA, range (0–66) [33]) and WOLF motor function test (WOLF, [34]). FMA scores were divided [35] into a distal portion (shoulder, elbow and forearm 0–34, A), a wrist portion (0–10, B), a hand portion (0–16, C), and a coordination/speed portion (0–6, D). This analytical evaluation was carried out in order to understand how overall improvements (if detected) could be credited to one portion or another. In order to allow comparison among the different portions, the related scores were normalized with respect to their maximum values.

C. Statistical Analysis

Due to the small sample size and the fact that data do not have a normal distribution, statistical differences were first evaluated for each clinical measure (FMA, WOLF and FMA subportions) at the three times of analysis (T0, T1 and T2) using a nonparametric test, namely the two-tailed Friedman test. Post-hoc analysis was performed using Wilcoxon signed rank tests in order to find out differences between T0 and T1 (related to the overall efficacy of the treatment), T0 and T2 (for assessing the persistence of the improvements), and T1 and T2 (for checking possible changes during the rest period). Bonferroni correction was used, testing the hypotheses with a 0.0167 significance level.

As regards the RoM, in order to test the short term effect of the treatment, we performed a three-way ANOVA evaluating three factors: the session-factor (1:10), i.e., the potential improvement after a single training session; the TIME of measurement factor (PRE/POST); and the DoF-factor (FE, AA, PS).

For both the RoM and RoAM, a two-way ANOVA was used in order to detect differences of the means for each DoF (factor 1: FE/AA/SP), related to the different times of analysis (factor 2: T0/T1/T2 for the RoM and T0/T1 for the RoAM). Newman-Keuls *post hoc* analysis with Bonferroni adjustments ($p = 0.0167$) was performed to infer differences among the assessments instants.

IV. Results

All subjects enrolled in this study successfully completed the ten-session training protocol. They were allowed to rest between consecutive blocks of trials and among the three training modules for each DoF, in order to avoid muscular fatigue and attentional stress that could be detrimental for the consolidation of the functional gains. Over the course of the experiments, it was noticed that there was no degradation of performance and furthermore the order of presentation of training modalities (A, B or C) had no significant effect on overall performance.

Fig. 4 (top panels) shows a typical example of the functional recovery achieved by a subject for the FE training module, as a consequence of the progressive, adaptive training strategy. Panel A refers to the first training session and panel B to the final session. The top pair of figures show, for each block, the oscillatory trace of the target (in black) and the corresponding trace of the subject's average movement (in gray): the amplitude of the latter oscillation is smaller than the former one but the difference is smaller than the permitted threshold (2 deg). In the first session the subject could complete only eight blocks of trials and this number increased to 13 in the final block. Moreover, in the first session the trained oscillations ranged from 40 deg in flexion to 5 deg in extension whereas in the final session the

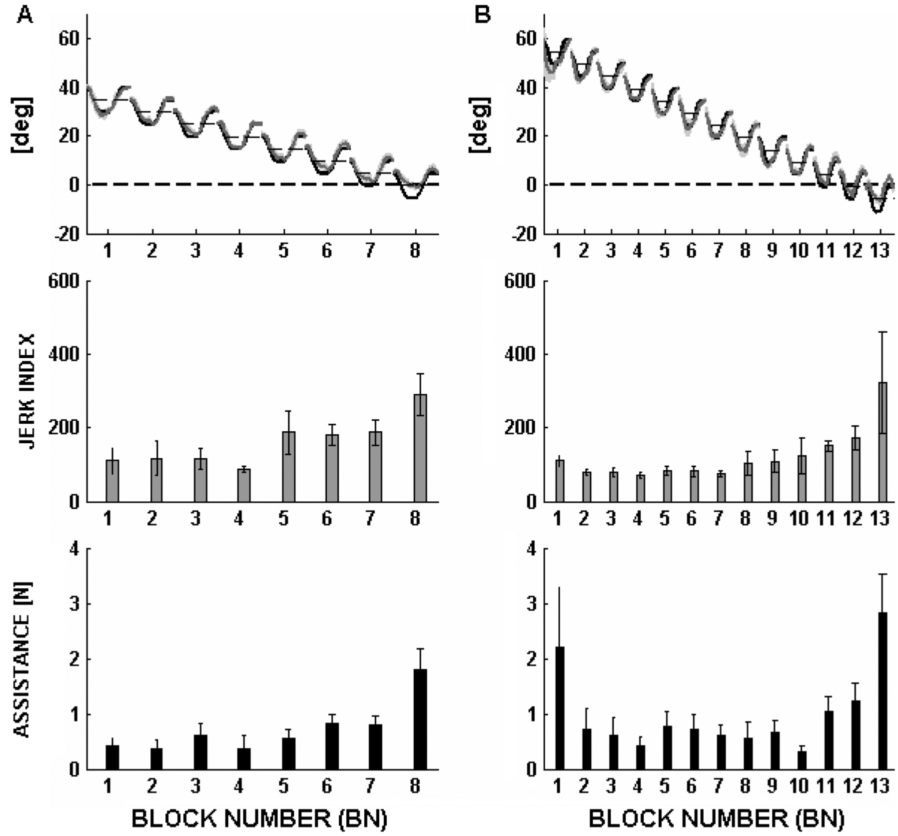

Fig. 4. Training performance for subject S2. The two series of panels (A and B) refer to the initial and final session for the FE training module. The pair of top panels display the motion pattern: the black paths represent the target oscillations for each block; dark gray paths represent the average trajectories of the subject, with the corresponding standard error (light gray shaded); the dashed black lines identify the bias or offset angles of the harmonic target trajectory in each block. At the end of each successfully completed block, the bias angle is changed by a 5° in a staircase-like fashion, which scans the RoM from easier to more difficult anatomical configurations. The horizontal black dashed line sited at zero angular value represents the threshold between flexion (positive values) and the extension (negative values). The improved performance of this subject from the first to the last session can be described by observing the following items: 1) the initial offset angle increases from 35° to 55°; 2) the number of completed blocks increases from 8 to 13 and so the RoAM increases from 45° (which is almost 35% of the entire allowed RoM) to 70° (which is almost 54% of the same RoM). The pair of middle panels represent the average jerk index for each block of movements, with the corresponding standard error. The pair of bottom panels are the average assistive torques for each block of movements.

range was increased from 60 deg in flexion to 10 deg in extension; in other words, training determined a quite larger RoAM. This also means that the RoM measured in the final session is substantially greater than the RoM of the initial session, because the RoM measurement, performed in the test phase of a session, is used to define the initial offset of the training sessions.

The middle panels show the jerk index and the bottom pair the value of the assistive torque in the different blocks of trials. The jerk index does not significantly change over the course of trials except in the most peripheral part of the range of motion where the spasticity of the articulation prevent the subject to move in a smother way.

It is worth mentioning the average value of the jerk index (for the FE motion) was slightly smaller in the final session than in the first one (191.83 ± 26.40 versus 194.58 ± 23.90) but without showing a statistically significant difference, and similar pattern was found for AA (112.52 ± 8.26 versus 127.79 ± 20.80) and PS (400.23 ± 60.76 versus 426.68 ± 65.04). The relative higher difficulty in performing the training movements over the boundary portion of the RoM can be explained observing the higher rate of the provided assistive torque. However, if one considers the average values of the assistive torque in the final session versus the initial session no significant differences are present for FE motion (0.81 ± 0.10 N/m versus 0.94 ± 0.15 N/m), AA motion (3.17 ± 0.34 N/m versus 2.71 ± 0.08 N/m), and PS motion (0.78 ± 0.08 N/m versus 0.81 ± 0.10 N/m): this result does not mean an inefficacy of the treatment characterized by a reduced recovery of subjects' voluntary capacity of motion, but contrarily a constant level of robotic assistance allows to patients to reach a wider portion of their range of motion over the course of the therapy. The aforementioned data refer to a single subject (S2, with reference to Table I), but for all the subjects we observed a similar results as regards jerk and torque.

A. Robotic Outcomes

1) Short Term Effect in RoM Restoration (Single Session): In order to test the effectiveness of the robotic therapy, we measured at the beginning and at the end of each therapeutic session and for the whole therapy, for each DoF, the RoM of the subjects by asking them to actively oscillate back and forth a given DoF in such a way as to achieve the largest possible range; the robot encoders were used for the measurements, with no robotic assistance. The measures were normalized with respect to the entire RoM allowed by the device and we evaluated: 1) the *single-session effect*, by comparing the estimated values before (PRE) and after (POST) training sessions [Fig. 5(A)] and 2) the *overall*

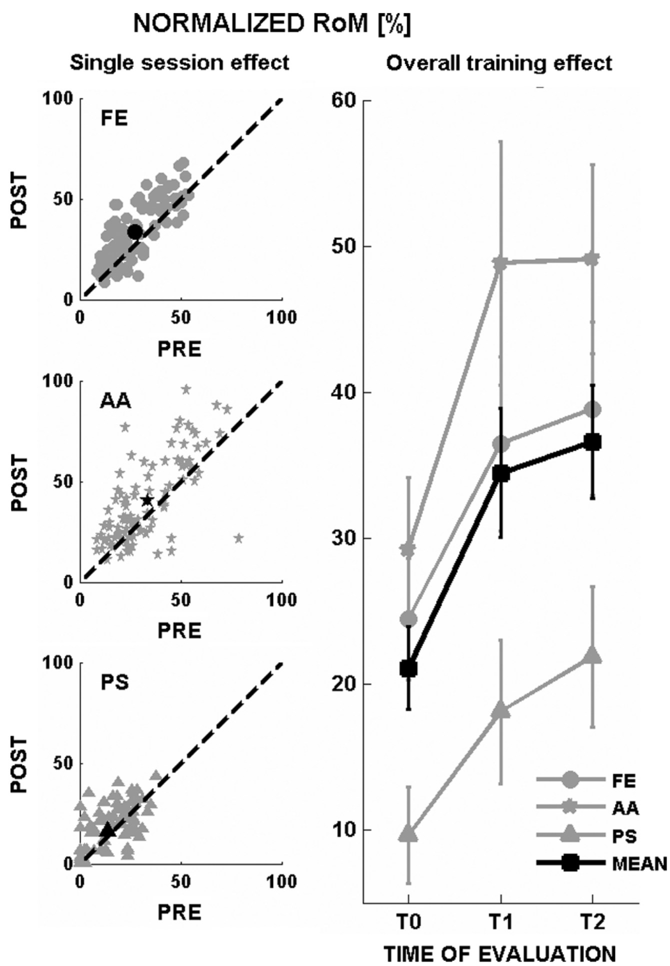

Fig. 5. (A) Single session effect on the normalized RoM. Normalization is carried out with respect to the entire range allowed by the device for each DoF: FE, AA, and PS, respectively. Symbols in each graph represent the performance of a subject in a single session, PRE versus POST, for a given DoF: each graph contains 90 points, that is nine subjects × ten sessions. A data point located above the equality line (dashed, with a slope of 45 degrees) indicates that a subject had a higher RoM value in the POST than in the PRE test phase, meaning an increased RoM at the end of the single therapy session. The opposite would hold for a point below the equality line The black markers represent group means. (B) Overall training effect on the normalized RoM. Time series evolution of the population means (±SE) during the whole ten training and test procedures, for each DoF (gray symbols) and overall averaged performance (black symbol). **T0**: before training; **T1**: end of training; **T2**: at follow-up.

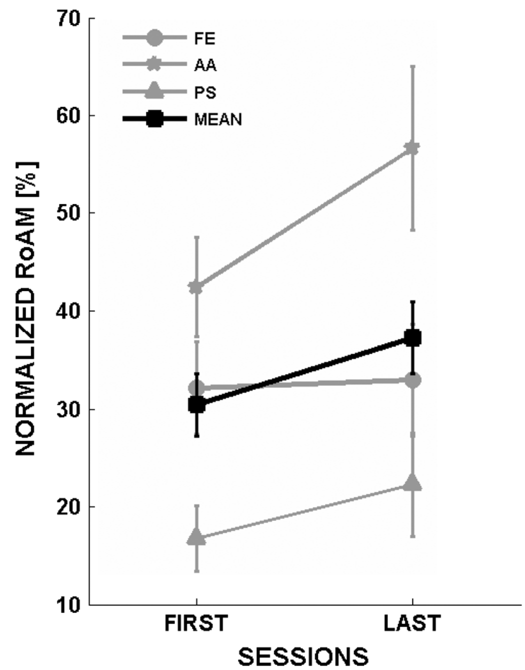

Fig. 6. Evolution of the RoAM, normalized with respect to the entire range of motion allowed by the device. Mean group values of the percentage ratio of ROAM described during the first (FIRST) and last session (LAST) for all the subjects. Grey symbols represents different tasks (FE, AA, PS), while black squares represent the average value over the three DoFs. Error bars indicate ± SE.

training effect, by plotting the average population values against the three reference times T0, T1, T2 [Fig. 5(B)].

As regards the single-session effect, Fig. 5(A), which plots PRE (initial) versus POST (final) RoM values of all the subjects for each DoF, clearly shows that most of subjects' performance fell above the dashed equality line, i.e., POST $>$ PRE: 67 out of 90 ROM measurements (74.4%) for the FE task, 65 out of 90 (72.2%) for the AA task, and 59 out of 90 (65.5%) for the PS task. This is also confirmed by the analysis of the normalized RoM population mean (depicted as black markers): $30.12 \pm 1.17\%$ (POST) versus $24.58 \pm 0.97\%$ (PRE). A three-way ANOVA (10 session × 3 DoF × 2 time) revealed significant differences between the three measures within a single session $(\mathrm{F}(1,8) = 17.956, \mathrm{p} = 0.00285)$, with a short term benefit for each training. Considering the outcomes of the whole rehabilitation protocol the analysis highlighted statistically significant differences among sessions $(\mathrm{F}(9,72) = 4.1303, \mathrm{p} = 0.00026)$ and DoFs $(\mathrm{F}(2,16) = 19.012, \mathrm{p} = 0.00006)$. Observing the black markers in Fig. 5(A), it is clear that PS movements exhibit a smaller single-session effect than FE and AA: in fact, while the normalized average values of the RoM for FE and AA were $30.37 \pm 1.08\%$ and $36.74 \pm 1.43\%$, respectively, the average PS RoM was $14.95 \pm 0.85\%$.

As regards the effect observed over the course of the training, Fig. 5(B) shows the evolution of the normalized RoM estimates from the first session (T0), to the last session (T1), and then to the follow up test (T2). A two-way ANOVA [factors: 3 time of evaluation (T0, T1, T2) × 3 DoF (FE, AA, PS)] revealed significant differences among the three DoFs $(\mathrm{F}(2,16) = 22.28, \mathrm{p} = 0.00002)$, where AA showed the highest value of restored RoM $(42.36 \pm 4.16\%)$, FE a lower percentage $(33.26 \pm 3.25\%)$ and the PS a quite limited improvement $(16.53 \pm 2.64\%)$ of the entire allowed joint's excursion. Moreover, also the time of evaluation factor was statistically significant $(\mathrm{F}(2,16) = 15.80, \mathrm{p} = 0.00016)$ highlighting that the RoM increased between T0 and T1 (*post hoc* analysis by Newman-Keuls; $\mathrm{p} = 0.000522$) and improvements were present in the follow-up too (T0 versus T2, $\mathrm{p} = 0.000389$; T1 versus T2, $\mathrm{p} > 0.05$).

2) Training Phase: During the training phase, we evaluate online the range of motion for each DoF reached by means of robotic assistance (RoAM Fig. 6): the above-mentioned measure provides a quantification of the subject's limit of voluntary capacity in executing the required task because a high control effort by the device indicates a high level of assistance needed. A

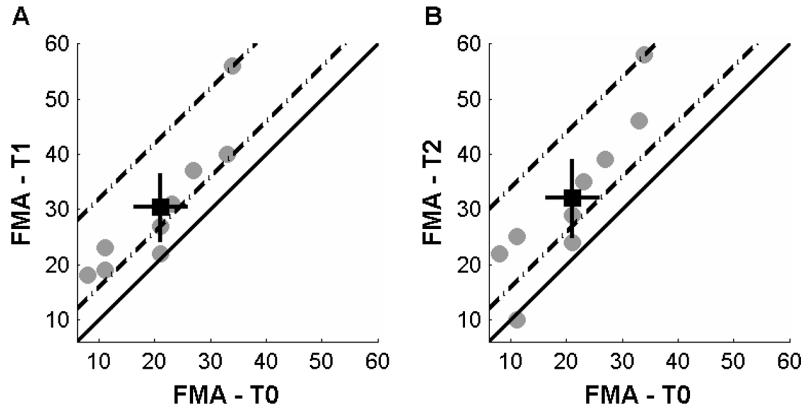

Fig. 7. Modifications of the FMA score. (A) between T0 and T1; B: between T0 and T2. Each gray circle in the graph represents a subject. The bold line from the origin, with a 45 degree slope (equality line), identifies the locus of points for which there is no difference in the FMA score between T0 and T1 (or T2). Subjects who exhibit a beneficial effect from the exposure to the training protocol are represented by circles above the line; the opposite indicates subjects who did not improve over the training. The two black squared markers are the averages for the corresponding task and their associated standard errors. The two dotted lines mark off the range of improvement between 6 and 22 points for (A) and between 6 and 14 points for (B) respectively and experimentally obtained during data analysis. **T0**: before training; **T1**: end of training; **T2**: at follow-up.

two-way ANOVA with factors session (FIRST and LAST) and DoF (FE, AA, PS) was performed in order to understand if the normalized RoAM increased significantly during a single session. The analysis revealed a statistical significance $(\mathrm{F}(2,16) = 22.61, \mathrm{p} < 0.001)$ for the main factor DoF, highlighting the fact that subjects responded differently to the therapy for the three DoFs: AA reached almost 50% $(49.52 \pm 5.06\%)$, FE covered $32.54 \pm 3.60\%$ of the entire space and finally the PS motion had a percentage of $19.50 \pm 3.12\%$ of assisted range of motion.

B. Clinical Outcomes

1) FMA Assessment: Overall Treatment Effect: Fig. 7(A) shows how the FMA score changed between T0 and T1 for all the subjects. All of them fall well above the equality line and the population mean increased from 21.00 ± 3.17 to 30.22 ± 4.10 points. Moreover, for eight out of nine patients the increase was higher than 3.7 ± 0.5 points, which is considered as the threshold for achieving significant functional recovery [36]. Actually, for eight subjects, the change was higher than six points and the average of the total FMA score for the group was 9.33 ± 1.89.

Fig. 7(B) shows that in eight out of nine subjects the FMA score at follow-up (T2) was higher than at T0; in the ninth subject the score at T2 was only marginally worse than at T0. For the population, the improvement was 11.00 ± 2.39 points; again, for eight out of nine subjects the improvement was higher than seven points. Statistical analysis revealed a significant difference among the three evaluation times (T0, T1 and T2) $(\mathrm{p} = 0.002)$. The Wilcoxon *post hoc* analysis detected significant relationships between T0 and T1 $(\mathrm{p} = 0.004)$ and T0 and T2 $(\mathrm{p} = 0.009)$, while the difference between T1 and T2 was not significant ($p > 0.05$), meaning that the motor recovery induced by the training was maintained also at follow-up.

Table II shows the detailed distribution of FMA scores for all the subjects at the three evaluation times.

2) WOLF Motor Function Assessment: Fig. 8 shows the evolution of the WOLF clinical scale from T0 to T2 for all the subjects. It illustrates that overall there is an improvement in the functional use of the upper extremity as effect of the treatment (see Table III and Fig. 8). The statistical analysis (Friedman test) revealed a significant difference among the three assessments at T0, T1, and T2 $(\mathrm{p} = 0.005)$. The *post hoc* analysis (Wilcoxon signed rank *post hoc*) reported that the gap between T0 and T1 was statistically significant $(\mathrm{p} = 0.016)$, meaning that the treatment had beneficial effects on WOLF scale. Moreover, this improvements were observed after three months $(\mathrm{T0\text{-}T2} : \mathrm{p} = 0.008))$ and the score at the follow up (T2) persisted after the end of the training cycle $(\mathrm{T1\text{-}T2} : \mathrm{p} > 0.05)$.

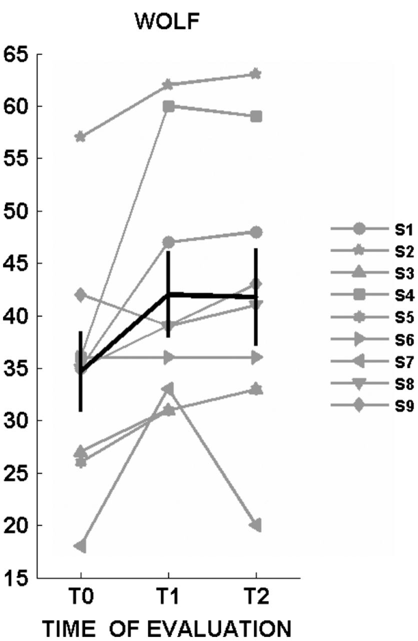

Fig. 8. WOLF motor function test. Changes in the WOLF score for the nine subjects (gray lines and different markers) and its average values ± SE (black line). **T0**: before training; **T1**: end of training; **T2**: at follow-up.

Summing up, the improvements reported by the analysis of the instrumental measurements of RoM and RoAM (see Figs. 5 and 6) are clearly correlated with the functional improvements detected by the clinical scales (see Figs. 7 and 8). This satisfies one of the basic goals of this pilot study.

TABLE II

CHANGES IN FUGL-MEYER CLINICAL SCALE. FOR EACH SUBJECT, TABLE PRESENTS FIVE VALUES: TOTAL FMA SCORE (TOT) AND SUBPORTION: A = SHOULDER/ELBOW/FOREARM, B = WRIST, C = HAND, D = COORDINATION/SPEED. GREY COLUMNS REPRESENT THESE VALUES. WHITE COLUMNS SHOW DELTA BETWEEN THE DIFFERENT TIMES OF EVALUATION (T0, T1, AND T2). LAST FOUR ROWS ARE AVERAGE VALUES ± STANDARD ERROR

		T0	**T1**	**T1-T0**	**T2**	**T2-T1**	**T2-T0**
S1	A	15	22	7	22	0	7
	B	0	0	0	2	2	2
	C	1	1	0	1	0	0
	D	5	4	-1	4	0	-1
	TOT	**21**	**27**	**6**	**29**	**2**	**8**
S2	A	16	20	4	22	6	2
	B	5	6	1	9	4	3
	C	8	11	3	12	4	1
	D	4	3	-1	3	-1	0
	TOT	**33**	**40**	**7**	**46**	**6**	**13**
S3	A	8	16	8	18	10	2
	B	0	2	2	2	2	0
	C	0	0	0	2	2	2
	D	0	0	0	0	0	0
	TOT	**8**	**18**	**10**	**22**	**4**	**14**
S4	A	20	31	11	31	11	0
	B	3	9	6	9	6	0
	C	6	11	5	13	7	2
	D	5	5	0	5	0	0
	TOT	**34**	**56**	**22**	**58**	**2**	**24**
S5	A	10	20	10	21	11	1
	B	0	0	0	0	0	0
	C	1	3	2	4	3	1
	D	0	0	0	0	0	0
	TOT	**11**	**23**	**12**	**25**	**2**	**14**
S6	A	14	12	-2	14	0	2
	B	0	1	1	4	4	3
	C	2	3	1	2	0	-1
	D	5	6	1	4	-1	-2
	TOT	**21**	**22**	**1**	**24**	**2**	**3**
S7	A	8	16	8	8	-1	-8
	B	0	0	0	0	0	0
	C	2	3	1	2	0	-1
	D	1	0	-1	0	-1	0
	TOT	**11**	**19**	**8**	**10**	**-9**	**-1**
S8	A	21	27	6	29	8	2
	B	2	4	2	2	0	-2
	C	1	3	2	4	3	1
	D	3	3	0	4	1	1
	TOT	**27**	**37**	**10**	**39**	**2**	**12**
S9	A	15	26	11	27	12	1
	B	3	0	-3	0	-3	0
	C	2	2	0	5	3	3
	D	3	3	0	3	0	0
	TOT	**23**	**31**	**8**	**35**	**4**	**12**
MEAN	A	14.11±1.58	21.11±2.02	7.00±1.36	21.33±2.44	6.33±1.77	1.00±1.30
	B	1.44±0.63	2.44±1.08	1.00±0.80	3.11±1.19	1.67±0.91	0.67±0.55
	C	2.56±0.88	4.11±1.35	1.56±0.56	5.00±1.48	2.44±0.77	0.89±0.45
	D	2.89±0.70	2.67±0.74	-0.22±0.22	2.56±0.67	-0.22±0.22	-0.22±0.28
	TOT	**21.00±3.17**	**30.33±4.10**	**9.33±1.89**	**32.00±4.77**	**1.671.41**	**11.00±2.39**

3) FMA Assessment: Carry Over Effects From Distal to Proximal DoFs: The previously considered clinical scales (FMA and Wolf) provide a global assessment that does not distinguish between functional improvements related to the proximal versus distal DoFs. On the other hand, the proposed robot therapy system did not address the proximal DoFs. Nevertheless, some studies [11], [15]–[17] support the hypothesis that there might be a carry over or generalization effect from trained to untrained DoFs. For this reason, we exploited the fact that the FMA score, which has a range from 0 to 66, has been conceived as an overall assessment that combines analytical evaluations of different body parts/function: FMA-A (elbow/forearm: range 0–34); FMA-B (wrist: range 0–10); FMA-C (hand: range 0–16), FMA-D (coordination/speed: range 0–6). We normalized the FMA subscores by dividing the therapist's assessments with the corresponding subscore range. The analysis of the data between T0 and T1 shows that improvements were found in all the sections: FMA-A $(\mathrm{T1\text{-}T0} : 7.00 \pm 1.37)$, FMA-B $(\mathrm{T1\text{-}T0} : 1.00 \pm 0.80)$, FMA-C $(\mathrm{T1\text{-}T0} : 1.56 \pm 0.56)$ and FMA-D $(\mathrm{T1\text{-}T0} : 0.22 \pm 1.89)$ (Fig. 9).

While the percentage for sector D slightly decreased from T0 to T1 $(\mathrm{T0} : 48.15 \pm 11.60, \mathrm{T1} = 44.44 \pm 12.42\%)$, the other FMA sectors showed a raising trend $(\mathrm{T0} : 41.50 \pm 4.64\%, 14.44 \pm 6.26\%, 15.97 \pm 5.52\%$ and $\mathrm{T1} : 62.09 \pm 5.95\%, 24.44 \pm 10.82\%, 25.69 \pm 8.43\%$ for sectors A, B, and C, respectively) and the improvement was kept also at the follow up T2 ($62.75 \pm 7.17\%, 31.11 \pm 11.95\%$ and $31.25 \pm 9.26\%$, respectively for A, B, and C). In order to test the significance of the improvements for the percentage ratio of each session, we performed the Friedman test for each subportion. The time of evaluation resulted in a statistically significant factor for the subportion A (elbow/forearm, $\mathrm{p} = 0.005$) and subportion C (hand, $\mathrm{p} = 0.012$).

TABLE III
CHANGES IN WOLF CLINICAL SCALE. GREY COLUMNS REPRESENT THESE VALUES. WHITE COLUMNS SHOW DELTA BETWEEN THE DIFFERENT TIMES OF EVALUATION (T0, T1, AND T2). LAST ROW REPRESENTS AVERAGE VALUES ± STANDARD ERROR

	T0	T1	T1-T0	T2	T2-T0	T2-T1
S1	35	47	12	48	13	1
S2	57	62	5	63	6	1
S3	27	31	4	33	6	2
S4	36	60	24	59	23	-1
S5	26	31	5	33	7	2
S6	36	36	0	36	0	0
S7	18	33	15	20	2	-13
S8	35	39	4	41	6	2
S9	42	39	-3	43	1	4
MEAN	34.7±5.5	42.0±5.9	7. 3±4.1	41.8±6.7	7.1±3.6	-0.2±2.5

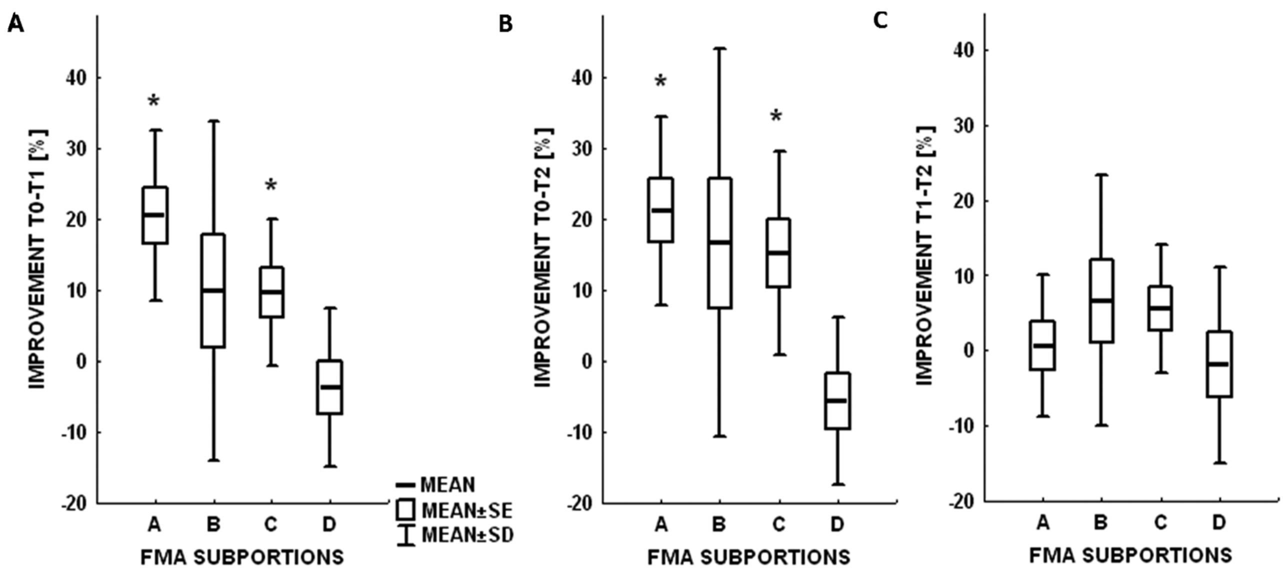

Fig. 9. Percentage improvements in the FMA subportions. Three panels represent percentage improvements between T0 and T1 (A), T0 and T2 (B), T1 and T2 (C), for each of the four subportions of the FMA score: A (elbow/forearm); B (wrist); C (hand), D (coordination/speed). Black horizontal segment inside the rectangular box represents the average population value, the vertical limits of the box illustrate the MEAN± SE and the black lines outside define MEAN± SD. The * symbols show statistical significant changes.

Summing up, the data exhibit a significant carry over effect because the distal DoFs (shoulder, elbow and hand) did improve although they were not specifically involved in the robotics protocol, as shown by the *post hoc* analysis: both subscore FMA-A and FMA-C revealed a tangible increase of the ratios between T0 and T1 $(p = 0.004)$ and between T0 and T2 $(p = 0.008)$ [see Fig. 9(A) and (B)], while no significant difference was found between T1 and T2 [Fig. 9(C)]. Somehow surprisingly, FMA-A was indeed the subscore that exhibited the highest improvement.

V. DISCUSSION

A strategy of adaptive, progressive training of wrist movements for chronic stroke patients has been proposed and its efficacy has been tested by means of a preliminary clinical investigation with a population of nine patients, trained over ten sessions. The main result of the study is that chronic stroke patients are able to recover and improve motor functions for distal and proximal limb sectors and both robotic data and clinical evaluations based on impairment and functional assessments (FMA and WOLF respectively) reported a positive trend and significant differences over the entire protocol and follow-up too.

A. Skill Transfer From Distal to Proximal Limb

Between initial and final phase of the protocol (T0-T1), on the average the clinical score FMA significantly increased by 9.33 ± 1.89 points: this improvement exceeds the minimum change of 3.7 ± 0.5 points, which is considered necessary to achieve significant functional recovery [36], suggesting a noticeable reduction of motor impairments of the related joints as well as an improvement in the voluntary motor functions after training.

In line with the improved upper limb functions, we found beneficial effects for functional use of the upper extremity as measured by Wolf motor function test. However, it is not clear if these positive changes in motor impairments and functional measures translate into increased use of the affected upper extremity in day-to-day life.

The reported clinical results are particularly remarkable because they involve proximal movements that were not explicitly comprised in the training protocol as demonstrated by FMA assessment for shoulder and elbow with a relatively high score change (from 41.50% to 62.09%) suggesting that training distal segments may also induce skill transfer to the proximal parts [9], [13], [17], [18].

This effect may be due to different causes; distal movements activate nerves and muscles that control the whole upper limb [18], for example, the biceps is involved not only to supinate the forearm and but also to flex the elbow and shoulder; alternatively, patients might have tried to develop compensatory strategies to achieve forearm movements with their shoulder and body trunk [37]. We might reject this last hypothesis because subjects' shoulder was firmly hold by means of suitable casts and orthosis during the robotic therapy sessions. We can also speculate that the generalization of motor improvements can be attributed to the larger activation of the sensorimotor cortex resulting from distal upper limb exercise [17].

B. Short and Long Term Improvements of RoM

In chronic stroke patients, there is frequently a systematic postural bias of the wrist, characterized by exaggerated flexion, adduction, and pronation, which is associated with a strongly reduced RoM and hypertonia. The consequence is that the wrist mobility is "frozen" in an unnatural posture: the hand cannot be engaged in functional actions and thus the whole upper arm is cut off from skilled activities of daily life. The haptic robot-patient interaction employed in this study was designed in such a way to "unfreeze" the impaired DoFs allowing them to be recruited in functional activities.

To assess improvements in the range of motion that subjects can freely cover, we measured the RoM before and after each of the ten sessions. Data showed an increased RoM after a single training, indicating that the gentle interaction between the robot and the human wrist helps subjects to decrease spasticity and hypertonia and augments the mobility of the wrist.

We found that the effectiveness of the training technique was not equal for all the exercised degrees of freedom; in fact, we measured the highest increase in RoM for abduction/adduction whereas pronation/supination showed the least significant results. As a matter of fact, wrist rotation around a longitudinal axis can only be achieved in an indirect manner by the pronation/supination action of the radio-ulnar joints, with contributions from biceps/triceps muscles and the shoulder if further rotation is required [2], hence such complex movement can be difficult to perform for stroke patients reducing the chance of success for robotic assistance. The reported evidence in motor recovery transfer from distal to proximal upper limb may open new scenarios in the implementation of robotic therapeutic protocol. If on one side human hand and wrist represent the main anatomical parts responsible for interaction and manipulation in everyday life, on the other side the proximal limb functions cannot be exploited without fully recovered functionalities of the distal movements. Therefore, the main question is either upper limb rehabilitation therapy must treat specific anatomical joints separately, or exercising peripheral districts can strongly influence and provide beneficial effects to the more proximal arm.

One of the main features of the proposed robotic assistance mechanism is the use of assisted, small oscillations, which are progressively shifted from "easier" to "more difficult" postures. The results suggest that this approach is effective, but why does it work? A possible interpretation, which may cover at least part of the explanation of this complex phenomenon, comes from the physiology of immobilized muscles [38]: it is known indeed that muscle is a very adaptable tissue and even the number of active sarcomeres can be altered by a long lasting immobilization. Sarcomeres are added on, if a muscle is immobilized in the lengthened position, and are lost if it immobilization keeps the muscles in a shortened configuration [39], [40]. In stroke patients the muscles governing wrist movements are not physically immobilized but their mobility is strongly reduced by pathological patterns of muscle contractions and long inactivity, a sort of "functional immobilization" that in chronic patients is likely to have changed the properties of muscle tissues. Taking this into account, we may speculate that oscillatory robot assistance may have a double effect: 1) at the peripheral level, it may favor "sarcomerogenesis" [41], helping to recover more physiological muscle properties; 2) at the central level, it may stimulate the restoring of functional activation patterns, since the assisted movements are not passive but they require some level of active voluntary control.

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V. Squeri graduated in biomedical engineering at the University of Genova, Genova, Italy, in 2004, with a thesis concerning the analysis of upper arm's movements in patients with hemicrania and received the M.S. degree in bioengineering from the University of Genova, in 2006, studying the development and assessment of a robot therapy rehabilitation protocol for patients with Multiple Sclerosis. In 2010 she received the Ph.D. degree in humanoid technologies from the University of Genova, with a thesis concerning how to use robots to study sensorimotor performance and promote neuromotor recovery.

Currently, she has a Post Doctoral position at the Italian Institute of Technology (IIT), Genova. She has a strong background in haptics, upper limb rehabilitation robotics and implementation of assistive control algorithms.

L. Masia graduated in mechanical engineering at "Sapienza" University of Rome, in 2003, and received the Ph.D. degree in "mechanical measurement for engineering" from the University of Padua, in 2007, with the thesis "Design and characterization of a modular robot for hand rehabilitation."

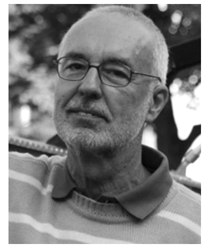
He was Ph.D. visiting student at the Massachusetts Institute of Technology, Cambridge, MA, USA (from January 2005 to December 2006) working at the Newman Lab for Biomechanics and Human Rehabilitation (Mechanical Engineering Department). He was a postdoctoral researcher (February 2007 to February 2011) and held a team leader position (March 2011 to July 2013) at the Robotics Brain and Cognitive Sciences Department of the Italian Institute of Technology leading the Motor Learning and Rehabilitation Laboratory, focusing his research on design and development of novel mechatronic devices for rehabilitation and haptics. He is currently an Assistant Professor at the School of Mechanical and Aerospace Engineering at Nanyang Technological University of Singapore. His background is in mechanical design, measurement, and control applied to human machine interaction with special emphasis to robotic rehabilitation with a scientific experience considerably enriched by multidisciplinary collaborations with other research teams from haptics and control engineering to biomechanics passing through robot aided technology with a long lasting experience in clinical applications.

P. Giannoni graduated in physiotherapy at the University of Genoa, Genova, Italy. She studied at the Bobath Centre of London and received the qualification as EBTA Bobath Tutor and IBITA Instructor in 1977 and 1985, respectively.

At the present she is Director of the ART Rehabilitation and Educational Center of Genoa, school for post-graduated physiotherapists and medical doctors, recognized by the Italian Health Minister. Her current interests include mainly the application of Bobath Concept in stroke patients and children with cerebral palsy along with robot therapy.

G. Sandini received the degree in electronic engineering (bioengineering) from the University of Genova, Genova, Italy, in 1976.

Until 1984, he was Research Fellow and Assistant Professor at the Scuola Normale Superiore, Pisa, Italy. After his return to the University of Genova as Associate Professor at the Faculty of Engineering, in 1990 he founded the Laboratory for Integrated Advanced Robotics (LIRA-Lab). Since 2006, he has been leading the Department of Robotics, Brain and Cognitive Sciences at the Italian Institute of Technology. His research activities are in the fields of biological and artificial vision, computational and cognitive neuroscience and robotics with the objective of understanding the neural mechanisms of human sensory-motor coordination and cognitive development from a biological and an artificial perspective.



P. Morasso graduated from the University of Genoa, Genova, Italy, in electronic engineering, in 1968.

He was a Postdoctoral Researcher and Research Fellow at Massachusetts Institute of Technology, Boston, MA, USA, in the lab of Prof. Emilio Bizzi. He was formerly a Full Professor of Anthropomorphic Robotics at the University of Genoa, and is now a Senior Researcher at the Robotics, Brain and Cognitive Sciences Department, Italian Institute of Technology. At the University of Genoa, he directed the Doctoral School in Robotics and the course of study in biomedical engineering. His current interests include neural control of movement, motor learning, haptic perception, robot therapy, and robot cognition.