Translational effects of robot mediated therapy in subacute stroke patients: an experimental evaluation of upper limb motor recovery

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Robot-mediated therapies enhance the recovery of post-stroke patients with motor deficits. Repetitive and repeatable exercises are essential for rehabilitation following brain damage or other disorders that impact the central nervous system, as plasticity permits to reorganize its neural structure, fostering motor relearning. Despite so many studies that claim the validity of robot mediated therapy in post-stroke patient rehabilitation, it is still difficult to assess to what extent its adoption improves the efficacy of traditional therapy in daily life, and also because most of the studies involved planar robots. In this paper, we report the effects of a 20-session-rehabilitation project involving the Armeo Power robot, an assistive exoskeleton to perform 3D upper limb movements, in addition to conventional rehabilitation therapy, on 10 subacute stroke survivors. Patients were evaluated through clinical scales and a kinematic assessment of the upper limbs, both pre- and posttreatment. A set of indices based on the patients' 3D kinematic data, gathered from an optoelectronic system, was calculated. Statistical analysis showed a remarkable difference in most parameters between pre- and post-treatment. Significant correlations between the kinematic parameters and clinical scales were found. Our findings suggest that 3D robotmediated rehabilitation, in addition to conventional therapy, could represent an effective means for the recovery of upper limb disability. Kinematic assessment may represent a valid tool for objectively evaluating the efficacy of the rehabilitation treatment.



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14 Abstract

15 Robot-mediated therapies enhance the recovery of post-stroke patients with motor deficits. 16 Repetitive and repeatable exercises are essential for rehabilitation following brain damage or 17 other disorders that impact the central nervous system, as plasticity permits to reorganize its 18 neural structure, fostering motor relearning. Despite so many studies that claim the validity of 19 robot mediated therapy in post-stroke patient rehabilitation, it is still difficult to assess to what 20 extent its adoption improves the efficacy of traditional therapy in daily life, and also because 21 most of the studies involved planar robots. In this paper, we report the effects of a 20-session-22 rehabilitation project involving the Armeo Power robot, an assistive exoskeleton to perform 3D 23 upper limb movements, in addition to conventional rehabilitation therapy, on 10 subacute 24 stroke survivors. Patients were evaluated through clinical scales and a kinematic assessment of 25 the upper limbs, both pre- and post-treatment. A set of indices based on the patients' 3D 26 kinematic data, gathered from an optoelectronic system, was calculated. Statistical analysis 27 showed a remarkable difference in most parameters between pre- and post-treatment. 28 Significant correlations between the kinematic parameters and clinical scales were found. Our 29 findings suggest that 3D robot-mediated rehabilitation, in addition to conventional therapy, 30 could represent an effective means for the recovery of upper limb disability. Kinematic 31 assessment may represent a valid tool for objectively evaluating the efficacy of the 32 rehabilitation treatment.

33 **1.** Introduction

34 Stroke, both ischemic and hemorragic, affects about 10 million people every year 35 worldwide [1], representing the second most frequent cause of death, after coronary artery 36 disease and is the leading cause of disability in the elderly [2]. Many stroke survivors (about 42 37 million in 2015) [3] sustain neurological damage, which is often permanent. Among other 38 impairments, stroke can compromise use of the upper limbs, thereby negatively impacting 39 common daily living activities - (ADL) [4].

40 Although stroke patients are usually able to recover their ability to walk independently in 41 a relatively short time, thanks to advanced rehabilitation therapies, a complete recovery of 42 upper limb function is not as common [5]. Hence, effective therapies must be repetitive, target-43 oriented and intense, in order to stimulate the neural plasticity processes, and are fundamental 44 to the recovery of motor functionality [6]. Traditional therapy, manually administered by 45 rehabilitation operators, rarely meets all of these criteria. The introduction of assisted robot 46 therapy has improved the efficacy of upper limb rehabilitation and significantly improved the 47 living conditions of patients [7].

48 In recent years, technological advances, and increasing interest in robotic rehabilitation, 49 have led to the development of high performance machines that can provide support to the 50 rehabilitation operator; in some cases, they can even perform a perfectly complementary job 51 [8]. Since the 1990s, these devices have become more pervasive. The first models allowed the 52 operator to utilize pre-set tasks, and were activated "as needed" [9], [10], thereby allowing the 53 rehabilitation operator to follow multiple rehabilitation treatments simultaneously [11]. More 54 recently, robots have integrated rehabilitation strategies that adapt to patient feedback. For 55 example, robots can react to forces applied by the patient during rehabilitation [12].

An essential feature of robotic devices is the ability to perform repetitive movements over a long period of time. The repetition and intensity of exercises are crucial in rehabilitative therapies for patients affected by stroke or other neurological pathologies. Research has shown that neural plasticity is preserved after a brain injury, thereby allowing for new connections to form between the neurons while their gradual reorganization can restore movement and functionality to the affected limb [13]. Thanks to the virtual environments where exercises are 62 performed, in the form of games with specific goals, the patient is more immersed compared to63 traditional therapies, which constitutes a further benefit.

Noteworthy, examples of upper limb rehabilitation robots currently available on the market or in research laboratories include the MIT-Manus for the end-effector typology [14], [15], and the Armeo®Power exoskeleton (Hocoma, Inc.) [16], which is derived from the research prototype Armin [17], [18]. The latter has been involved in studies that introduced a novel rehabilitation solution to foster neural plasticity, which showed promising results derived from transcranial magnetic stimulation [19].

Rehabilitation mediated by robots also provides quantitative results about improvements in task execution, thereby allowing researchers to quantitatively monitor the recovery of limb functionality [20]. These performance indicators represent a fundamental method to evaluate the administration of specific rehabilitation protocols or the prescription of different exercises during rehabilitation. Performance data used to estimate the patient's motion capabilities can be obtained during specific exercises, via software installed on the device.

76 Considering this potential, robot mediated therapy (RMT) became prominent in research 77 activities that were focused on improving traditional rehabilitation paradigms [21]. Although 78 many studies to date have reported on the recovery of post-stroke patients treated through 79 RMT, it is still difficult to assess the extent to which these results go beyond traditional 80 therapies administered within a comparable timeframe [22]. In other words, despite the 81 greater level and quality of both support and stimulation provided to patient, and the 82 evaluating tools made available to clinicians, demonstrating higher effectiveness in recovery of 83 RMT with respect to traditional therapy is still an open challenge.

One reason for this lack of evidence lies in the heterogeneity of RMT solutions and, consequently, in the wide variety of strategies that have been proposed to evaluate its effects. To analyse pre-post treatment effects, many studies have combined a kinematic evaluation of patients' motor performance compared to traditional evaluation techniques, in an effort to overcome the intrinsic challenges associated with replicating clinical scales [23]. In fact, despite being designed to comprehensively evaluate different aspects of motor deficit resulting from a stroke, clinical scales are prone to uncommon sensitivity, ceiling effects, and subjectivity in their

administration by the operator [24][25][26]. However, in most cases, this type of
supplementary metric is calculated on the same gestures performed for the treatment.
Consequently, in order to reveal the translational effects of rehabilitation, an evaluation of the
motor performance regained by the patients should involve gestures that mirror daily activities,
and are derived from the RMT scenario [27].

96 Several studies have assessed the possibility of using a kinematic evaluation based on a 97 simple daily-life inspired gesture, to objectively assess stroke-related motor impairment. van 98 Kordelaar et al. proposed evaluating kinematic parameters that are based on the hand 99 trajectory recorded by an electromagnetic motion tracking device, during a simple exercise 100 based on reaching and moving objects on a table [28]. A similar paradigm, was proposed by 101 Rohrer et al., that assessed motion smoothness changes during recovery in the aftermath of a 102 stroke, by leveraging a MIT-Manus [25]. However, these movements are planar and the gravity 103 load effect is supported by the robot or by the table. In contrast, a 3-DoF protocol would 104 facilitate an evaluation of the final effect of recovery, where the force exerted for a vertical 105 elevation of the hand plays an important role. Caimmi et al. proposed a 3-DoF protocol where 106 the subject was tasked with reaching towards a target placed in front of him at shoulder level 107 and starting from a lower position. Kinematic indices, based on motion capturing, 108 demonstrated improvements for stroke survivors thanks to constraint-induced movement 109 therapy [29].

110 In this paper, we adopted a protocol similar to the one introduced in [29], for evaluating 111 the translational effects of an RMT-based rehabilitation project and administrated to ten stroke 112 survivors, using a rehabilitation exoskeleton: the ARMEO Power device. In particular, we 113 primarily sought to investigate whether kinematic indices, based on motion capturing a 3D 114 daily-life inspired gesture, improved after the administration of an RMT protocol, which 115 involved an exoskeleton for 3D upper limb rehabilitation. As a secondary goal, we evaluated 116 how these indices are in agreement with patient assessments that have been evaluated using 117 the most widely-adopted clinical scales for post-stroke motor impairment.

118 **2.** Methods

119	2.1. Patients' description
120	Ten subjects (8 males and two females, mean age 60.1 \pm 18.3 years) affected by stroke in
121	the sub-acute phase (4.0 \pm 1.5 months after the event; 5 with left and 5 with right hemiparesis)
122	were enrolled in the study.
123	Inclusion criteria were:
124	• unilateral paresis from a single supratentorial stroke occurring at least six months prior;
125	 sufficient cognition to follow simple instructions and understand the purpose of the
126	study (Mini-Mental State Examination, MMSE score > 18 points) [8];
127	 ability to perform the task proposed (pointing a target, with the unaffected and with
128	affected limb);
129	 ability to remain in a sitting posture.
130	Exclusion criteria were:
131	 participation in other studies or rehabilitation programs;
132	bilateral impairment;
133	 severe spasticity (Modified Ashworth Scale score ≥ 3);
134	 severe sensory deficits in the paretic upper limb;
135	• other neurological, neuromuscular or orthopedic (shoulder sub-luxation or pain in the
136	upper limb) disorders, or visual deficit;
137	 refusal or inability to provide informed consent;
138	other concurrent severe medical problems.
139	Table 1 reports the primary clinical data of the patients included in the study. Patients
140	were clinically evaluated using the four most adopted rating scales in stroke: the motor sub-
141	section of the Functional Independence Measure (FIM) [30], Barthel Index (BI)[31], Frenchay
142	Arm Test (FAT) [32], and Fugl-Meyer Assessment (FMA, Motor function sections, maximum

- 143 score 66) [33].
- 144

145 **2.2. Treatment protocol and device**

146 This study was performed in accordance with the Declaration of Helsinki and was

approved by the ethics committees of IRCCS Centro neurolesi Bonino Pulejo (study registration
number 43/2013). Informed consent was obtained from all subjects enrolled in this study.

Patients underwent a rehabilitation program of 20 sessions, each lasting 50 minutes, five sessions per week, using the Armeo®Power exoskeleton, in addition to a session of conventional rehabilitation therapies conducted with the same duration.

The Armeo[®]Power (Figure 1) is a motorized orthosis for the upper limb with six degrees of freedom (DoFs): three DoFs for the shoulder, one for the elbow flexion, one for the forearm supination, and one for the wrist flexion. Each joint is powered by a motor and equipped with two angle sensors.

The device can support the patient's arm weight, thereby providing a feeling of fluctuation, and assists it in a large 3D workspace during execution of the exercises. The presence of a suspension system allows the facilitator to set and adjust the sensitivity of the robot depending on the characteristics of each patient. Arm and forearm lengths are both adjustable, so that the device can be adapted for use by a large selection of patients.

The interface used for the execution of exercises, which appear in the form of games, is designed to simulate arm gestures and provide a simple virtual environment. Increasing levels of difficulty can be selected, which in turn determines the speed of the movements, their direction and the work area, depending on the degree of motility of the subject undergoing rehabilitation.

Each robotic session, which lasted 50 minutes, consisted of: 10 minutes of passive mobilization for familiarization and to decrease the patient's spasticity, if present; and 40 minutes of task-oriented exercises that were calibrated according to the patient's abilities and with increasing difficulty over the course of the training period.

170 **2.3.** Experimental setup for kinematic analysis

To evaluate the effects of the prescribed treatment, patients underwent a 3D kinematic analysis, both pre- and post-treatment. Patient movements were recorded during a pointing task (Figure 2), using an Optoelectronic System (OS), the BTS SMART-DX 300 [34], which consists of six infrared CCD cameras with a resolution of 650x480 pixels, and an acquisition rate of 120 Hz. In this study, a subset of the kinematic model proposed by G. Rab [35] has been adopted, to ensure the optimal execution of the exercise. In particular, the head, neck and pelvis segments have been removed. Reflective markers were placed on the patient's body, referenced in the model (Figure 3). The wrist joint is modelled as a universal (saddle) joint with two-degrees-of-freedom, where wrist movement occurs in flexion-extension and radio-ulnar deviation; the elbow like a hinge joint with two degrees of freedom; the shoulder as a spherical joint with three degrees of freedom.

The pointing task designed for 3D kinematics acquisition required reaching a target, placed on the subject's sagittal plane, at shoulder height, and at a distance from the body equal to the patient's arm length (measured from the acromion marker to the midpoint between the radius and ulna markers). The patient was sitting on a chair with his hands stretched along his hips and his back resting but not locked in that position, thereby allowing compensatory movements, which were also measured (Figure 2).

Each of the two kinematic evaluations (pre- and post-treatment) were recorded in a session in which the patient was invited to reach and point at the target from a neutral position, without straining, first with the healthy limb and then with the paretic one. Repeating the task six times took about 10 minutes.

193 2.4. Data processing and statistical analysis

194 Three-dimensional marker trajectories were recorded using frame-by-frame acquisition 195 software (SMART Capture – BTS, Milan, Italy) and labelled using frame-by-frame tracking 196 software (SMART Tracker – BTS, Milan, Italy). The captured data were transferred to MATLAB 197 software (The Mathwors Inc., Natick, Massachusetts), were interpolated and filtered with a 6 198 Hz second-order Butterworth filter in both forward and reverse directions, resulting in a zero-199 phase distortion and fourth order filtering.

The velocity of the hand marker was computed using numerical differentiation. Movement onset was defined at the time when the velocity of the hand marker exceeded 5% of the maximum velocity in the pointing phase. Movement offset was detected when the velocity of the hand was below the threshold previously described [36].

204 Kinematic data of the session were processed to calculate the following indices:

205 206	 Movement time (MT), as the total execution time of the task (between onset and offset), measured in seconds [5], [37]–[39];
207 208	• Peak velocity (PV), as the maximum value of the speed profile curve of the hand marker, measured in meters per second [37], [40]–[44];
209 210	• Time to PV (TtPV), as the percentage of time from the beginning of the movement to the peak speed [37], [43];
211212213214	 Normalized Jerk (NJ), as a non-dimensional quantity which corresponds to the square root of the jerk (third derivative of the position of the hand marker with respect to time), mediated over the entire duration of the movement, and normalized with respect to MT and to the total displacement of the onset and offsets (L) [41], [42], [45];
215216217218	 Trunk Displacement (TD), measured in meters to identify compensation movements, calculated as the difference between the maximum displacement of the trunk marker and its initial position in space, normalized with respect to distance C7-sacrum, expressed as a percentage [37], [40], [41];
219220221	• Hand Path Ratio (HPR) is the ratio of the distance travelled by the hand between the movement onset and offset and the straight-line distance between the starting and destination targets, expressed as a percentage [40], [43], [44], [46].
222 223 224	MT, PV, and TtPV indices are related to the time required for pointing at the target and the speed at which the task is performed. NJ quantifies the fluidity of motion: higher values correspond to lower smoothness,

reflecting poor fluidity in motion, or absence of fine tuning of muscular control, whereas a fluid movement will be expressed by a lower value. Although other indices of smoothness have been proven valuable during the last few years [47], today NJ is the most widely adopted index for smoothness.

TD provides information about the compensation strategies implemented by the patient during execution of the task.



231 HPR, instead is considered an index of motion accuracy in point-to-point movements [48]. 232 Statistical analyses were performed with SPSS software (Statistical Packages for Social 233 Sciences, version 24.0, SPSS Inc., Chicago, IL). Considering the non-normal distribution of the 234 indices and the small size of the sample, non-parametric tests with a 95% confidence interval (α 235 = 0.05) were applied. In particular, the Wilcoxon signed-rank test 2-tailed was chosen to verify 236 whether there were differences between pre- and post-treatment for each parameter. The 237 Spearman correlation test was performed to highlight any correlation between kinematic 238 parameters and the main clinical scales used.

239 **3. Results**

240 An example of reaching trajectories, obtained during the evaluation tasks, is depicted in 241 Figure 4. Figure 5 reports mean and standard deviation values of the NJ calculated on hand 242 trajectories during each task repetition. Significant differences between pre- and post-243 treatment kinematic indices were found for MT (Z = -2.701, p = 0.007), NJ (Z = -2.701, p =244 0.007), TD (Z = -2.701, p = 0.007), and HPR (Z = -2.701, p = 0.007). The average values of all 245 these parameters were lower after the treatment than before, as reported in Figure 6. No 246 significant difference was found for PV, and TtPv between the pre- and post-treatment 247 evaluations. As displayed in Figure 5 and Figure 6, the values of the indices, derived from the 248 affected arm, are reported along with values obtained from the unaffected arm, to visually 249 compare the difference in the indices and illustrate improvement.

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All of the administered clinical assessment scales resulted in pre- vs. post-treatment significant decrease: FIM (Z = -2.803, p = 0.005), BI (Z = -2.809, p = 0.005), FAT (Z = -2.831, p = 0.005), FMA (Z = -2.807, p = 0.005), as reported in Table 2.

Table 3 reports the results of the Spearman correlation test, across all kinematic parameters and all administered clinical assessment scales. A strong tangentially significant correlation was found between FAT and HPR. A moderate, yet insignificant, correlation (0.40 < |rs| < 0.59), was found between BI and MT, BI and TD, FAT and TtPV, and FMA and HPR.

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259 4. Discussion

In this study, we analysed the effects of robot mediated therapy conducted with an exoskeleton that supported the 3D movement of the upper limbs, involved ten stroke survivors, using a pre- vs. post-treatment 3D kinematic analysis of a specific upper limb gesture, which mirrored a daily living activity. Their residual motion capabilities were evaluated by means of a set of kinematic parameters that were measured during execution of a reaching task with both the paretic and the unaffected arm, other than by using the four most adopted clinical scales.

266 Our findings demonstrate the benefits of a rehabilitation program focused on the range 267 of motion capabilities of post-stroke patients. Indeed, these patients demonstrated an 268 improvement across all administered clinical scales, and these results are in agreement with the 269 kinematic analysis conducted. The trajectories of reaching tasks performed after treatment 270 were smoother and more accurate. Four out of the six kinematic indices computed on the 271 reaching trajectories travelled after the treatment of the paretic arm were different to those 272 obtained before the treatment. In particular, indices obtained with the paretic arm, after the 273 treatment, showed movement more comparable to the unaffected arm.

274 The significant decrease in MT indicates regained mobility with gesture performance. A 275 reduced time to complete the task implies a more effective combination of motion smoothness and accuracy. Regardless of the actual distribution of improvement from these two aspects, the 276 277 overall ability to complete the task in a reduced timeframe indicates an increase in patient 278 independence in daily life, which is a key concern in rehabilitation. Frisoli et al. [38] 279 demonstrated a significant correlation with the total time for the reaching movement with the 280 clinical evaluation of motor impairment in both ischemic and hemorrhagic stroke patients. This 281 index showed a significant decrease after a rehabilitation program, towards the value observed 282 in healthy control group.

NJ is generally understood as an index of motion smoothness, where higher levels of this parameter are typical of less smoothly controlled gestures [49]. All of the patients showed a noticeable decrease in the NJ average value in reaching tasks performed with the paretic arm. Values of NJ obtained after the RMT program, are closer to those performed with the unaffected arm.

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Conversely, HPR represents the subject's ability to perform a reaching trajectory within

the shortest possible distance between the start and target points. A line connecting the two points does not exactly represent the path chosen by unimpaired subjects, as shown in Figure 3. However, the difference between the actual hand trajectory and the line is an important parameter in evaluating accuracy in reaching tasks [39]. Stroke survivors who participated in our study exhibited a significant decrease in this index in post-treatment trials compared to pretreatment ones, with an average value more comparable with that of the unaffected arm.

Another significant improvement was observed in the TD index for our sample study. This result can be interpreted as a secondary effect of the restoration of motor activation paths from the motor cortex to muscles. The increased capability of the subject to fire the necessary motor units required less compensatory trunk muscle activity to complete the task [50]. Murphy *et al.*, demonstrated that TD is significantly higher in post-stoke patients than in healthy subjects, and a noteable increase in this index can also be observed between patients with moderate stroke with respect to those with a mild stroke.

Interestingly, no significant effect was observed in PV and TtPV. Although these are generally considered indices of motor capability in point-to-point tasks [37], the patients involved in this study did not exhibit any significant variation in these two indices. The restored motor control, highlighted by other observed markers, both clinical and kinematic, was not reflected in the velocity profile of the hand during specific pointing tasks. Thus, our preliminary findings suggests that one should not simply rely on these two indices as effective measurements for the effectiveness of a rehabilitation program.

309 Although the results were obtained from a small patient sample, the findings of the 310 present study are particularly important to current discussions about robot mediated therapy. 311 Moreover, to date, several studies have assessed improvements in the motion capabilities of 312 stroke survivors after RMT treatments, for a larger cohort of subjects [51]. However, 313 improvement has mainly been evaluated by means of clinical rating scales or kinematic indices 314 computed on gesture trajectories performed during rehabilitation treatment. Thus, it is 315 generally accepted that training stroke survivors to perform specific upper arm trajectories, in a 316 controlled and assisted manner that is facilitated by a robotic device, leads to improvement in 317 performing a specific task. However, a key issue with motor rehabilitation is the translational

effect of therapy, i.e. the potential to improve gestures typically associated with daily life, distinct from those performed in a rehabilitation program [52]. This problem is of great importance in analysing the robot mediated therapy effect throughout the entire rehabilitation process. Current studies only merely use the robotic device as as a theraputic instrument, while the kinematic evaluation was used to evaluate a simple gesture, which was highly representative of a daily life scenario.

324 Despite the number of RMT studies conducted thus far, proving increased performance 325 compared to a traditional rehabilitation program, within the same timeframe, remains a 326 challenge [22]. One reason is the lack of a standardized evaluation protocol for measuring the 327 impact, apart from the use of clinical scales. Although highly comprehensive and well 328 structured, clinical scales are not an objective tool, and are often comprised of different 329 characteristics related to disability, ranging from motor capabilities to facial expressions or 330 psychological treats. The protocol presented in this study has the potential to serve as a 331 standard evaluation tool for more objectively quantifying upper limb motor smoothness and 332 accuracy, derived from a rehabilitation program, and ultimately inspiring comparative studies 333 on the efficacy of RMT versus traditional therapy. Several studies have examined the pointing 334 movement in stroke patients [37], [38], [40], [53]-[55], however they have used different 335 kinematic variables to analyse the movement, despite the common goal of being able to 336 quantify speed, accuracy and fluidity of movement. In this vein, a comparative analysis of 337 patient behaviour in kinematic evaluation, in terms of clinical scales score, is of great 338 importance.

The kinematic evaluation protocol that we adopted, instead, was introduced by Caimmi et al [56], to evaluate the effects of constraint-induced therapy. In this study, we used this method to evaluate effects of RMT sessions, performed using a rehabilitation exoskeleton that induces 3D movements of the upper limb. Reporting these findings is valuable as the literature is lacking when it comes to these types of studies, especially with RMT solutions inducing planar movements, where the gravity effect is completely supported. The adoption of 3D robotics, assisting the subjects in compensating for gravity, is expected to enhance this capability.

346 To consolidate the preliminary findings of this study, and positively contribute to the

current discussions about the impact of RMT, future studies should involve a larger patient sample, in parallel with a control group undergoing conventional therapy. If confirmed on a larger number of patients, the positive results reported herein will pave the way for the establishment of a standardized procedure for objectively evaluating motor recovery in conjunction with a robotic rehabilitation program. This tool would have a tremendous potential in facilitating comparative studies about the effects of RMT compared to traditional physical therapy for rehabilitation.

354 Moreover, apart from the advantaged documented in this paper, as in other similar 355 studies, it is not possible to isolate the effects of RMT per se. A physiological progressive 356 improvement in the motor capabilities of stroke survivors, during the subacute phase, has 357 already been demonstrated [27]. Thus, a comparative study with only two groups of stroke 358 survivors would be required, where one group is treated with RMT, which would accurately 359 quantify the benefits of RMT, although this would be questionable in terms of ethics. 360 Ultimately, reporting the results of a specific therapy, using a standard protocol and a set of 361 accepted indices, is valuable, as it permits a better interpretation of the actual outcomes of the 362 therapy.

363 **5.** Conclusions

In this study, we analysed the effects of robot-mediated therapy on ten stroke survivors, through a pre- vs. post-treatment 3D kinematic analysis of a specific upper limb gesture, simulating daily living activities. Their residual motion capabilities were evaluated by means of a set of kinematic parameters measured during the execution of a reaching task with both a paretic and an unaffected arm.

369 Our results highlighted the efficacy of a rehabilitation program that benefits the motion 370 capabilities of patients. Patients exhibited improvements in all of the administered clinical 371 scales, which was in agreement with the kinematic analysis conducted.

Although the analysis was obtained from a small sample of patients, the findings of our study have the potential to contribute to the current discussions about robot-mediated therapy. The protocol presented in this study, inspired by daily-life gestures (upper limb motor tasks), may represent a step forward in establishing a standard evaluation procedure, for the 376 objective quantification of upper limb motor recovery following RMT-based treatments.

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Figure 1

The Hocoma Armeo®Power

A six degrees of freedom (DoFs) exoskeleton: three DoFs for the shoulder, one for the elbow flexion, one for the forearm supination, and one for the wrist flexion. Each joint is powered by a motor and equipped with two angle sensors (Photo: E F Russo).

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Figure 2

Subject performing the reaching task

Reflective markers are placed on the body according to the kinematic model adopted. A reflective marker is also placed on the target, installed on a rod in front of the subject, at the height of the shoulders. The rod was moved at every trial to align the target with the shoulder performing the reaching task (Photo: E F Russo).

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Figure 3

Kinematic model for reflective marker placement adopted in this study

12 markers (14 mm diameter) are placed over prominent bony landmarks of the upper extremity, easily identifiable and reproducible, where subcutaneous tissue is thin, minimizing soft tissue artifact due to marker movement with respect to bone.



Figure 4

Example of hand trajectories

Hand trajectories (in blue) during the reaching task, with respect to the shortest path (in red). (A): Reaching trajectory of the paretic arm before the treatment. (B): Reaching trajectory of the paretic arm after the treatment. (C): Trajectory of the unaffected arm.



Figure 5

Mean value of the NJ of hand trajectories for the ten patients across the different trials

The bars represent the standard deviation (\pm) . For each patient, values obtained with the affected arm before the treatment (green) are compared to those obtained with the same arm after the treatment (blue). Values obtained with the unaffected arm are also reported for visual comparison (yellow).



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Figure 6

Mean values of the six kinematic indices calculated across all the patients

Error bars represent the standard deviation (\pm) . For each index, mean values obtained with the affected arm before the treatment are depicted in green. Values obtained with the same arm after the treatment are reported in blue. Statistical significance between the two conditions are starred. For visual comparison, values obtained with the non affected arm are also reported in yellow.



Table 1(on next page)

Clinical data of the patients' population

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Patient	Gender	Age	Affected side	Months after event
1	М	66	Left	5
2	F	56	Right	2
3	М	40	Left	5
4	М	74	Left	5
5	М	73	Right	4
6	М	54	Right	4
7	М	65	Left	2
8	М	21	Right	2
9	М	69	Right	6
10	F	83	Left	5

1



Table 2(on next page)

Spearman correlation coefficients and significance level (in brackets) between the 4 clinical scales score and kinematic parameters, evaluated post-treatment

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Scale	Pre-treatment	Post-treatment	<i>n</i> value	
FIM	78.5±19.1	98.7±13.6	0.005	_
BI	52.5±21.1	75.5±14.0	0.005	
FAT	1.5±1.4	4.2±1.1	0.005	
FMA	32.6±13.9	45±10.7	0.005	
FAT FMA	1.5±1.4 32.6±13.9	4.2±1.1 45±10.7	0.005 0.005	_

1



Table 3(on next page)

Pre-treatment and post-treatment values (mean \pm standard deviation) of clinical scales

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	Index					
Scale	MT	PV	Τ _τ ΡV	NJ	TD	HPR
FM	-0.164	0.024	0.359	-0.207	-0.140	-0.049
	(0.650)	(0.947)	(0.309)	(0.567)	(0.699)	(0.894)
BI	-0.470	0.384	-0.049	-0.396	-0.511	0.024
	(0.171)	(0.273)	(0.894)	(0.257)	(0.131)	(0.947)
FAT	-0.192	-0.096	0.528	-0.329	0.364	-0.624 [⊤]
	(0.595)	(0.792)	(0.117)	(0.353)	(0.301)	0.054
FMA	-0.036	-0.120	0.164	0	0.152	-0.426
	(0.920)	(0.973)	(0.650)	1	(0.674)	(0.220)

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