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Improving the ROM of Wrist Movements in Stroke Patients by means of a Haptic Wrist Robot

Valentina Squeri, Lorenzo Masia, Laura Taverna and Pietro Morasso

***Abstract*—A 3 DoFs haptic wrist robot is used to measure and/or assist the movement of the wrist on three axes: flexion/extension (F/E), abduction/adduction (A/A), pronation/ supination (P/S). An assistance scheme based on the widely used progressive splinting therapy is proposed and its efficacy is tested within a group of nine chronic stroke patients, during a pilot study consisting of 2 sessions. Preliminary outcomes show that the technique is effective with the very distal part of wrist involving F/E and A/A but results in a reduced motor improvement for the P/S where proximal part of the arm is involved.**

I. Introduction

Over the last two decades robotic rehabilitation of the upper limb in neurological patients was mainly focused on proximal movements of the arm (shoulder and elbow). A smaller number of systems and preliminary clinical studies were addressed recover motor function of distal part such as wrist and/or hand: a representative set of studies is provided by [1-7]. Moreover, a recent meta-analysis [8] suggested significant improvement for patients trained with devices that targeted movement of the shoulders and elbows, whereas training with devices involving wrists and hand was less convincing. Therefore, there is still a lot of work to do with regard to the development of both better systems and better robot-patient interaction mechanisms. In this paper we report a preliminary study with a wrist robot which is a refined version of the device described in [5, 6].

II. Methods

A. Subjects

Nine stroke subjects (6 females and 3 males; age=29-72 years) volunteered to participate to this preliminary study. A neurologist and two physiotherapists 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); 4) stable clinical conditions for at least one month before entering robot therapy. Table I summarizes anagraphic and clinical data, including the clinical scores (etiology, disease duration, affected side, Fugl Meyer and Ashworth scores). For each subject we also evaluated the maximum values of flexion, extension, abduction, adduction, pronation, and supination, respectively. 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 that conforms to these guidelines. The robot training sessions were carried out at the Motor Learning and Rehabilitation Lab of IIT (Genoa, Italy), under the supervision of an experienced physiotherapist and with the help of a physiotherapy student.

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TABLE I
Clinical Data of the Subjects

Subj	Gender	Age	Side	Onset	FMA	WFMT	MAS
S1	F	49	L	8	8	26	3
S2	M	72	L	4	33	57	1+
S3	F	63	L	4	21	36	1+
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	R	6	27	37	1
S8	F	57	R	3	23	42	1+
S9	M	63	L	9	17	31	3

Subj: subject number; **Gender** (M/F); **Age**: years; Paretic **Side**: R/L; Time since **Onset**; years; **FMA** (Fugl-Meyer Arm section): 0-66; **WFMT** (Wolf Function Motor Test):0-85; **MAS**: (Modified Ashworth Scale): 0-4.

B. Experimental setup

The experimental setup (figure 1) consists of a wrist robotic exoskeleton with 3 degrees of freedoms (DoF) mounted on top of a planar 2 DoF manipulandum (BdF2, Celin Ltd, La Spezia, Italy) [9]. Although it can be used for a variety of assistive tasks, in this study the planar robot is only used for precisely supporting/positioning the wrist. The wrist robot

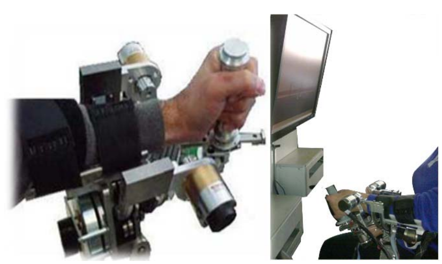

Figure 1. Experimental setup: IIT Wrist Robot (left panel) and mounted on top of the planar BdF2 robot (right panel).

allows the independent activation of three movements: F/E (Flexion/Extension), A/A (Adduction/Abduction, also known as Radial/Ulnar Deviation), P/S (Pronation/Supination). The subjects grasp a handle connected to the robot and their forearms are constrained by traps to a rigid holder in such a way that the biomechanical rotation axes are as close as possible to the robot ones. Unavoidable small misalignments are compensated by means of a sliding connection between the handle and the robot. The mechanical design allows a range of motion on the three DoFs (F/E: ±70deg; A/A: ±40deg; P/S: ±57deg) which approximately matches the range of healthy subjects [9].

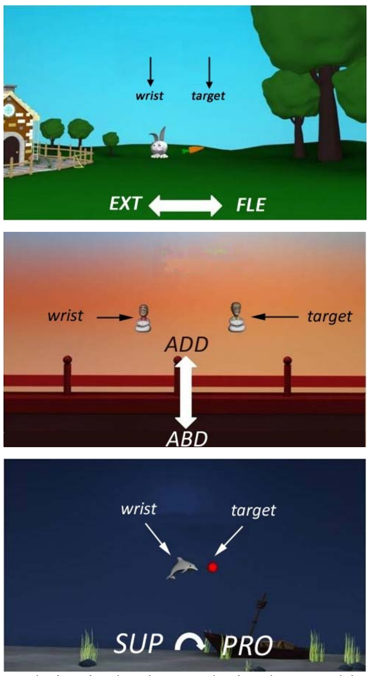

Figure 2. Visual rendering in the three tasks implemented in this study: ADD ABD (adduction/abduction); EXT FLE (flexion/extension); SUP PRO (pronation/supination).

Each DoF is measured by means of a high-resolution encoder (2048 bits/rev) and is actuated by one or two brushless motors, in a direct-drive, back-drivable connection. The control architecture integrates the wrist controller with a bi-dimensional visual virtual reality environment (VR) for showing to the subjects the position of the hand and the target against a nice-looking background, different in the three implemented experimental tasks.

C. Tasks

The assistive protocol trains one DoF at a time, with the task of tracking a sinusoidally moving target using the active DoF (A/A, F/E or P/S, respectively). Regular physical therapy of wrist rehabilitation consists in a splinting treatment for each single DoF at time, and there have been many studies that look at the splints' effectiveness and what type of splint would be best [10, 11]. For more than 20 years, clinicians have recognized the effectiveness of static progressive splints to improve passive range of motion (PROM). Dynamic splints use some additional component (springs, wires, rubber bands) to mobilize contracted joints [12]. This dynamic pull functions to provide a controlled gentle force to the soft tissue over long periods of time, which encourages tissue remodeling without tearing. The issues that make dynamic or static progressive splinting technically difficult include determining how much force to use, how to apply the force, how long to apply the force, and how to prevent added injury to the area. Things could change if the dynamic splinting is delivered using devices which are able to modulate torque delivering and space the range of motion. Therefore we intend to approach the robotic therapy for wrist rehabilitation using a continuous dynamic splinting of each single DoF but contrarily to the regular progressive splinting we want also to highlight the voluntary component of movement. This active assist exercise [13] helps the subject to complete the requested movement especially at the beginning but it didn't allow a passive completion of it. Moreover the design of the protocol also avoids the subject slows down in performance (Slacking Hypothesis, [14]) because as subject succeeded, task difficulty was increased (see below).

Figure 2 shows the graphical layout in the three cases. The current positions of the target and the wrist active DoF are visualized by means of specific markers, which move left/right in the F/E case, up/down in the A/A case, and on a circular path in the P/S case. The non active DoFs are kept fixed in the canonical position. In order to introduce in the protocol an element of soft/gentle assistance, we trained each DoF in steps or blocks of movements, with a limited amplitude at each step (±5deg). We also chose to progress from more natural to more difficult postures considering the trend in the range of motion for each trained DoF imposed by the hypertonicity (flexion → extension, abduction → adduction, and supination → pronation). More specifically, the motion of the target θ_{tg} that the patients were required to track was harmonic:

$$\theta_{tg}(t) = \theta_{off} + \theta_{ampl}\cos(2\pi t / T) \qquad (1)$$

with a period T=8s, amplitude θ_{ampl} =5deg, and bias or offset θ_{off}. At the beginning of the experimental run with one of the DoFs, the offset was set to the maximum values of flexion, abduction, or supination that each participant was able to freely reach with no device assistance. For each step, the subjects were requested to carry out 5 complete oscillations, with an assistive mechanism that included on-line monitoring of performance. More specifically, during each semi-oscillation, the target moved from θ_{off} to θ_{off} $\pm\theta_{ampl}$ in 2s according to eq. 1 and then the angular error (difference between the target and the wrist active angle) was measured: if such error exceeded a threshold of 2deg, the target stopped, waiting for the patient's attempt to complete the movement, up to a maximum waiting time of 4 s. An acoustic reward was given if the subject succeeded within the maximum allowed time and the current trial was counted as ‘completed’. Otherwise the trial was considered as ‘failed’. In both cases, however, the target started the following semi-oscillation. The block of movements terminated when the number of ‘completed’ movements reached the prescribed value of 10, i.e. 5 complete oscillations. As a consequence, each block of movement had a different duration, according to the subject performance. After a pause of 5s, the procedure was restarted, by shifting the offset by a quantity of 5deg, thus overlapping two consecutive steps by 50% of their oscillation amplitude. In other words, the entire RoM of each DoF was scanned in steps, by training the subjects from the ‘easier’ to the ‘more difficult’ angular configurations. The number of steps was not fixed but depended on the DoF and the performance of each subject for the given DoF, within the allowed training time of 15min per each DoF.

D. Robot assistance

The movements for each DoF were assisted by a combination of torques generated by the robot:

- An assistive component that helped the subject to complete the task. For F/E and A/A experiments, the assistive control law consisted of a non linear elastic field with a parabolic profile: the field that attracted the end-effector to the target was proportional the square of the distance between the measured angle and the target angle:

$$\tau = K(\theta_{tg} - \theta)^2 \, sign(\theta_{tg} - \theta) \qquad (2)$$

The gain K was set to 1Nm/rad^2 and 3Nm/rad^2 for the F/E and A/A DoFs, respectively. This force profile allowed a smooth interaction between robot and patient especially at the end of the movement. For the P/S DoF it turned out that a linear assistive field was sufficient:

$$\tau = K(\theta_{tg} - \theta) \qquad (3)$$

with a stiffness value of K=0.1 Nm/rad.

- A viscous component, with the purpose of damping small amplitude, high frequency oscillations:

$$\tau = B\dot{\theta} \qquad (4)$$

We chose the following values of the viscosity coefficient B: 0.001Nm/rad/s for F/E; 0.03 Nm/rad/s for A/A; 0.0001Nm/rad/s. for P/S, in order to provide a gentle intervention of the robotic assistance.

- an inertial compensation term, proportional to the angular acceleration, were added in the P/S case to overcome the mechanical impedance of the device and increase the backdriveability of the mentioned DoF.

E. Data analysis

The analysis was focused on the active voluntary RoM (Range of Motion) for each DoF, estimated at the beginning and the end of the training sessions: RoM_{Pre} and RoM_{Post}. To test the efficacy of the training sessions on the tested DoFs, we run an ANOVA with three factors: session (I and II); moment of the test (PRE-POST treatment) and DoF (F/E, A/A, P/S).

As regard the training phase, we evaluated: the number of blocks (NBL) that each subject finished for each DoF and the tracking error (TE [deg]) that is the difference between the moving target and the end-effector. We analyzed this two performance indexes with a mixed-model analysis of variance. This statistical analysis method was chosen for its flexibility to designs that are not perfectly balanced, as in our case. Moreover, it allows for taking into account the intrinsic (and uncontrolled) variability among the participants, which was considered everywhere as a random factor.

III. RESULTS

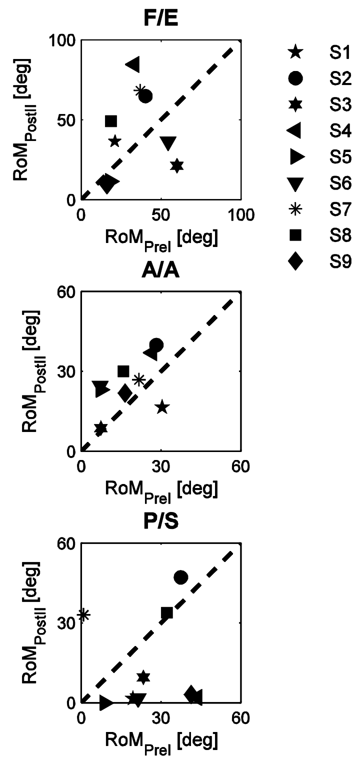

Figure 3. Relationship between the ROM before the initiation of the first training session and the end of the second session, for all the nine subjects and the three DoFs.

In this preliminary study, the subjects were exposed to two sessions of training. The main purpose was to verify the degree of acceptance by the subjects, the efficacy of the graphical interface, and the values of the assistance parameters. Figure 3 gives an overview of the modification of the RoM between the beginning and the end of this preliminary study, for the whole population of subjects. The dashed line is the set of points for which there is no difference pre-post training in the measured. This figure showed an improvement for the first two tested DoF: in the case of the F/E, the 55.5% of subjects placed above the equality line and the percentage increased to 88.9% for A/A. In the case of the P/S DoF the evidence is less positive (33.3%). Moreover, the statistical analysis showed that the PRE-POST difference is significant ($F(1,8)=6.6576$, $p=0.0326$) independent of the DoF and of the examined session.

As expected, there is also a significant difference ($F=12.80$, $p=0.0005$) with regards to the extent of the RoM, which is greatest in the F/E case (37.81±4.84 deg) and smaller in the A/A and P/S cases (23.83±2.55 deg and 19.18±2.81deg, respectively). The same trend was found for the number of blocks that subjects can complete in a DoF training. In fact the number of executed blocks is: 6.83±1.02, 4.9±0.6 and 3.2±0.7 for F/E, A/A and P/S respectively. These differences among the three DoFs resulted significant ($F=8.79$, $p=0.00$) running a two way ANOVA with session (I and II) and DoF (F/E, A/A, P/S) as factors.

Finally, there is a statistically significant ($F=5.44$, $p=0.047$) difference with regards to the tracking error, between the first and the second session: 3.22±0.03 and 2.88±0.02 respectively.

IV. Discussion and Conclusion

The results of our study show the feasibility of a robot-assisted therapy for the wrist with stroke patients.

A significant improvement in the free movement of the wrist (RoM) after a training session was observed. This result highlighted an efficacy of the exercise within the same session. To conclude about a long term effect of the training protocol we probably have to increase the number of tested sessions. However, we can observe a performance improvement from the first to the second session. In fact, during the second session, subjects were more accurate in following the moving target. This index showed a better control of the executed movement.

The three DoFs answered in different ways to the exercise. In fact the increase of free movement was bigger for the F/E and A/A DoF than for the P/S one. Also the number of blocks that subjects could complete was smaller in the case of the P/S DoF. The results emphasize the fact that all the subjects had more difficulties in completing the requested task during the P/S training than the other two; the main reason of this phenomenon may be due to the different afferent muscles on the three analysed DoFs. Although the human wrist is thought to have three degrees of freedom the Pronation-Supination mainly interests the distal radioulnar joint which is a pivot joint located between the bones of the forearm, the radius and ulna: this part is called extrinsic wrist and the muscles concurring in such kind of DoF are located in the middle part of the forearm. Contrarily the Flexion- Extension and the Abduction-Adduction are operated by the carpal bones and muscles forming the part called intrinsic wrist.

Concluding, the proposed training protocol for the wrist rehabilitation seems to be a promising therapeutic procedure for a future clinical study involving a bigger number of sessions and patients.

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