Project No. 231724

HUman behavioral Modeling for enhancing learning by Optimizing hUman-Robot interaction

HUMOUR

THEME 2: Cognitive Systems, Interaction, Robotics

Deliverable 7.2

Application of the HUMOUR framework in rehabilitation.

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PP	Restricted to other programme participants (including the Commission Service)	
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CO	Confidential, only for members of the consortium (including the Commission Service)	

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1 Introduction

The activities developed in WP7 (Optimal interaction in neuromotor rehabilitation) cover all applications in the domain of rehabilitation. In fact, the rehabilitation applications of the HUMOUR framework can be considered as the unifying thread connecting most of the work packages of the project.

The 'grand challenge' explored in WP7 was the ***Design of advanced approaches to robot-assisted neuro-rehabilitation***.

In particular the following hypotheses were tested:

- Can we identify a recovery strategy adopted by our patients during training?
- Can we use this strategy to optimize and adapt training based on the patient's performance?
- Can we maximize patient motivation and promote generalisation processes through varied therapy practice using a performance based regulation of training?
- How to regulate assistance to maximize recovery in tasks that involve multiple submovements?
- How do different patient characteristics influence motor recovery?

The robotic platforms used in the project as robot trainers were specifically designed and built for clinical and psychophysical research rehabilitation applications, and have been safely used in patient therapy and in studies in healthy humans. The robots provided passive (time triggered), active (activity triggered) or resistive exercise, depending on the amount of assistance required by the individual and the specific goals of the exercise. In addition, they allowed the implementation of varied therapy practice to promote generalisation processes. A second protocol tested how to regulate assistance to maximize recovery in tasks that involve multiple submovements and continuous regulation of assistance (assist-as-needed). The typical application scenario is represented in figure 1.

The use of different types of assistance means that our robots could be applied in a wider spectrum of patients. In fact, 'time triggered' assistance is suitable for more severely impaired patients who are able only to initiate movement. 'Negative' assistance, on the other hand, can improve the quality of movement in mildly impaired patients. 'Continuous' (assist-as-needed) and 'activity triggered' assistance should be considered a transition tool between the two previous types of assistance to progressively elicit and stimulate voluntary activity.
Within the HUMOUR framework further developments have been tested. In particular, the intention to move of the more impaired patients was detected using Brain Computer Interface technologies by the EKU partner to trigger a special orthosis for hand rehabilitation. This is a step beyond the experience reported in the literature to trigger the robot device through the EMG signal [1]. Conversely, the negative assistance has been extended by the use of virtual reality and gaming techniques as demonstrated in the experiments presented by the AAU partner in previous reports. It should improve patient engagement and motivation, so resulting in an improved outcome.

Finally, the results of the experiments carried out by Imperial College and IfADo in healthy subjects may find application in future training of patients.

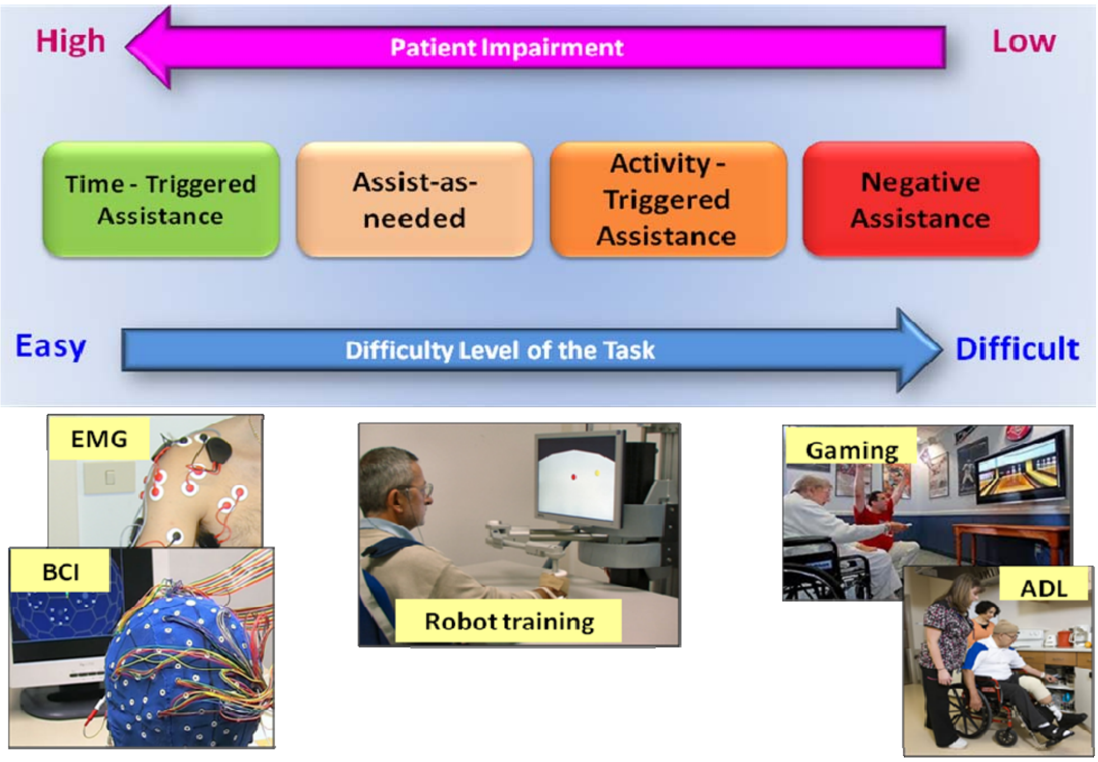


Figure 1. Different modes of assistance and difficulty levels of the tasks implemented in HUMOUR in relation to the level of impairment of the trained patients.

A special emphasis in WP7 has been placed on the identification of different patterns of temporal evolution of recovery in different categories of patients (e.g. chronic vs. sub-acute stroke survivors, severe vs. mild impaired, etc.). In fact, we think that if robotic neurorehabilitation provided by the HUMOUR framework has the advantage of allowing training to be customized to the patient's real needs and abilities, then awareness of how the different factors influence the time course of recovery is fundamental in order to adjust not only the features of the motor task but also other features of the training protocol such as training duration and intensity.

In the following paragraphs we provide an overview of the specific findings of experiments conducted in the neuromotor rehabilitation of patients.

2 The Progressive Training Regulation Algorithm (FSM)

In robot-assisted neurorehabilitation, matching the task difficulty level to the patient's needs and abilities, both initially and as the re-learning process progresses, can enhance the effectiveness of training and improve patients' motivation and outcome. Continuous challenging and assisting of the patient can substantially enhance the process of motor learning and improve motor coordination [2]. For this reason it is important to give subjects the right amount of assistance and an appropriate difficulty level of the motor task. Performance-based progressive training schemes have been proposed as a way to gradually reduce the amount of guidance during training [3], [4] . Basically, progressive control should permit the difficulty of the task to increase while at the same time assistance is gradually reduced. Algorithms adapting the difficulty level of the task have been proposed in applications of virtual reality technologies both for motor learning assessment and neurorehabilitation [5]. To our knowledge, current robotic devices providing assistance or associated control algorithms include different tasks and games but they do not offer the possibility of automatically changing the type of motor task administered or other features of the task in order to maintain a high level of patient involvement, and hence motivation, throughout the whole course of treatment.

In this project we implemented a Progressive Task Regulation (PTR) algorithm in a robot for upper limb rehabilitation. It evaluates the patient's performance during training through the computation of robot-measured parameters, and automatically changes the features of the reaching movements, adapting the difficulty level of the motor task to the patient's abilities. In particular, it can select different types of assistance (time-triggered, activity-triggered and negative assistance) and implement a varied therapy practice to promote generalisation processes.
The algorithm was developed and tuned by assessing the performance data obtained in 22 chronic stroke patients who underwent robotic rehabilitation in which the difficulty level of the task was manually adjusted by the therapist.

We observed in patients the existence of a recovery strategy consisting of concurrent optimization processes such as goal achievement, effort optimization and movement speed improvement, each having a different dynamic evolution as demonstrated by the different time constants; the former faster and the latter slower. This recovery strategy was used to choose the set of parameters estimating patients' performance to be included in the algorithm and to design the set of rules to identify the top/bottom level of adaptation in the parameters (steady performance) to optimize training.

The basic idea behind the PTR algorithm is to enhance patient motivation and the generalisation processes through varied therapy practice in the widest possible spectrum of patients. For this reason we designed the algorithm to provide different types of assistance and tasks. We generated a list of motor tasks with increasing difficulty level and designed the algorithm to regulate training by selecting the task and assistance that is most suitable for the patient's current ability, based on the performance obtained. This approach should overcome the shortcomings of previously presented algorithms aimed only at optimizing the level of assistance.

The algorithm we developed should be useful for the implementation of training protocols allowing individualized and gradual treatment of disabilities of upper limbs in patients after stroke. It is based on optimization principles of motor learning taking into consideration both patient and therapist behaviour, and has the potential to enhance the learning effectiveness of the administered tasks.
Details about the algorithm, its design and implementation strategies and a description of its application with previously recorded patient's performance data and in five chronic stroke patients in whom the algorithm conditioned the patients' behaviour ("closed loop" condition), can be found in the following papers:

I. Sterpi, A. Panarese, S. Micera, F. Pisano, R. Colombo. The Generalization of Motor Recovery After Stroke: Assessment Within and Outside the Training Workspace. *Submitted to BIOROB 2012.*

Colombo R., Sterpi I., Mazzone A., Delconte C., Pisano F. Development of a Progressive Task Regulation Algorithm for Robot-aided Rehabilitation. *Proceedings of the 33rd Annual International IEEE EMBS Conference*, August 30 - September 3, 2011, Boston, MA, USA.

R. Colombo, I. Sterpi, A. Mazzone, C. Delconte, F. Pisano. Taking a lesson from patients' recovery strategies to optimize training during robot-aided rehabilitation. *IEEE transaction on Neural Systems and Rehabilitation Engineering* . (In press)

Panarese A., Colombo R, Sterpi I., Pisano F., Micera S. Tracking Motor Improvement at Subtask Level During Robot-Aided Neurorehabilitation of Stroke Patients. *Neurorehabilitation Neural Repair* (In Press). DOI: 10.1177/1545968311431966

3 Protocol investigating how to regulate assistance in tasks that involve multiple submovements (IIT, FSM)

Many exercise protocols for robot therapy are designed to adjust their degree of difficulty in order to maintain a constant challenge level. A simple way to do this is to design exercises that consist of a variable number of sub-movements in different directions - task difficulty is determined by the number of sub-movements. But, how does recovery proceed in these tasks, and how to regulate the magnitude of the assistance provided by the robot in this case? Here we focus on a simple task in which subjects had to complete a square figure. At every trial, an adaptive regulator selects the appropriate degree of robot assistance needed to complete the entire figure. We tested this protocol with four severely impaired stroke survivors during a multisession study. Robotic training succeeded - the controller gradually reduced the degree of assistance while performance remained constant, suggesting that in fact recovery took place. We used a dynamic model of the recovery process to further analyze the effects of the assistive force and the temporal evolution of the subjects' voluntary control. The model provided an excellent fitting of the subjects' performance and revealed that magnitude and modalities of recovery are very different in the different sub-movements (Fig. 2). These results suggest that in order to maximize the recovery the modulation of assistance should occur at the level of each sub-movement.

Details about the preliminary results of this protocol can be found in the following paper:

V. Squeri, I. Sterpi, A. Basteris, M. Casadio, F. Pisano, R. Colombo, V. Sanguineti. Robot therapy for severely impaired stroke survivors: toward a concurrent regulation of task difficulty and degree of assistance. *Submitted to BIOROB 2012.*

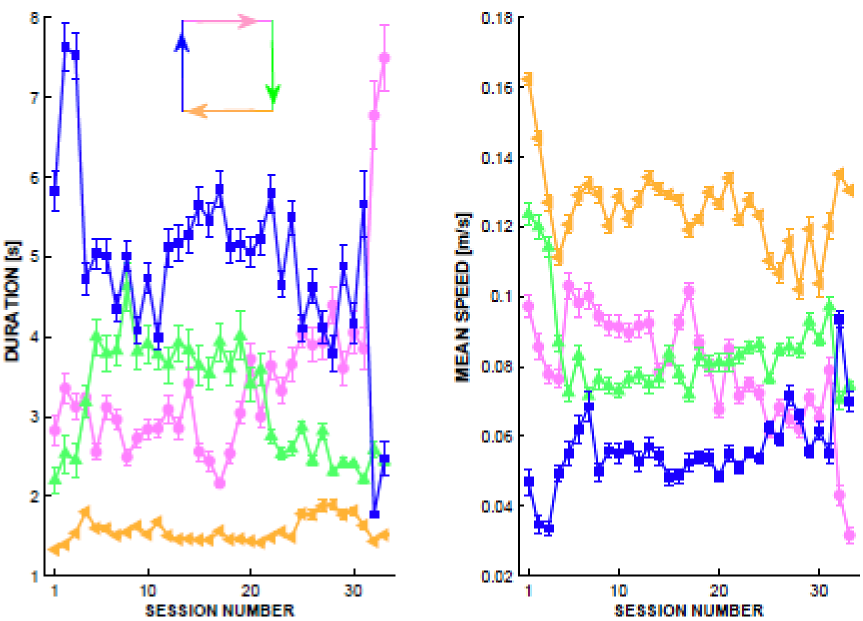


Figure 2. Movement duration (left) and average speed (right) varies greatly in different sub-movements. The different colours denote D1 (pink), D2 (green), D3 (orange), and D4 (blue).

4 Analysis of the performance acquisition model in sub-acute and chronic stroke patients (FSM)

Recovery from a stroke event is a complex process that likely occurs through a combination of spontaneous and learning mediated processes. Improvement with rehabilitation increases with the intensity of training and is related mainly to the tasks practiced during therapy. Knowledge of the pattern of recovery after stroke is helpful in determining when to expect recovery and in customizing appropriate treatment and timing of rehabilitation [6]. Some models have broken down post-stroke brain recovery into three partly overlapping epochs.

The first epoch is related to the acute event, the second to repair; most recovery and functional performance occurs in the first four weeks after stroke. A third epoch begins weeks to months after stroke when spontaneous behavioural gains have generally reached a plateau, and represents a stable but still modifiable chronic phase.

In a recent publication we showed that the performance improvement process in chronic patients after stroke can be considered as the result of different concurrent optimization processes starting at the same time but having different time constants [7]. Further, we used this knowledge to optimize and adapt training to patients with different abilities when a steady performance is detected. Even if it appears a general recovery strategy many other factors may influence the way patients recover after an acute cerebrovascular event. Given that robotic neurorehabilitation has the advantage that it allows training to be customized to the patient’s actual needs, the awareness of how the different factors influence the time course of recovery is fundamental.

A study was conducted in a group of 41 patients after stroke who underwent robot therapy of the upper limb. We analysed the time course of recovery of patients’ motor improvement by grouping subjects using the following different features: a) time since acute event (sub-acute <= 6 months; chronic > 6 months); b) impaired arm (Right; Left) c) level of impairment (FM <= 20; FM >20). The time course of recovery was evaluated by identifying the performance acquisition model (exponential model) of the Active Movement Index (AMI), Mean Velocity (MV), normalized Path Length (nPL), Mean Distance (MD) and Smoothness (SM) parameters during 30 training sessions in the above patient groups. The analysis carried out on the collected data resulted in the following findings:

1) All the performance acquisition models fitted the data very well; in fact high R squared values (0.8-0.99) were obtained for most of the above parameters.
2) Sub-acute patients had higher time constants than chronic patients; the difference was statistically significant for AMI and MV. Table 1 present details of this finding.
3) Left-arm impaired patients had higher time constants than right-arm impaired patients; the difference was statistically significant for MV and SM.
4) Highly impaired patients had higher time constants than mildly impaired patients; the difference was statistically significant only for SM.

The findings of this study have important implications for training of stroke patients using robot- assisted rehabilitation. In particular, sub-acute patients are characterized by a better outcome than chronic patients, but require a longer treatment period to reach the top level of learning, likely because of an interference phenomenon with the spontaneous recovery processes. In addition left-arm impaired patients require a longer period of training than right-arm impaired patients. Most of our patients were right dominant subjects; therefore it is likely that motor re-learning in the non dominant arm was slower than that for the dominant arm. Only the recovery of muscle synergies seems to be influenced by the level of impairment. These findings call for a strict customization of training using optimization principles of motor learning taking into account both patient and therapist behaviour so as to enhance the learning effectiveness of the administered tasks.

Table1. *Time constant and R^2 value of the exponential model fitted for the mean values of the performance parameters (AMI= Active Movement Index, MV=Mean Velocity, nPL=Normalized Path Length, MD=Mean distance) obtained for each training session during the course of recovery in the Sub-acute and Chronic Stroke patient groups. (* $p<0.05$).*

	Sub-Acute		**Chronic**	
	τ	R^2	τ	R^2
AMI	5.1*	0.97	2.7*	0.83
MV	12.1*	0.97	5.7*	0.96
nPL	3.5	0.97	3.7	0.85
MD	4.4	0.98	3.3	0.72

R. Colombo, I. Sterpi, A. Mazzone, C. Delconte, F. Pisano. Robot-assisted Neurorehabilitation in Sub-acute and Chronic Stroke Patients: how do different patient characteristics influence motor recovery? *(in preparation).*

5 Evaluation of patient motivation and adherence to the training program (FSM)

Motivation is an important factor in rehabilitation and is frequently used as a determinant of rehabilitation outcome [8]. In particular, active engagement towards a treatment/training intervention is usually equated with motivation, and passivity with lack of motivation. Consequently, high adherence to a rehabilitation program is seen as indicative of motivation [9]. In addition to personality and social factors, the design features of the biomedical robot can greatly influence the motivation and adherence of patients to robot-aided treatments. In particular the difficulty level of the motor task, the awareness of the performance obtained, and the quantity and quality of feedbacks presented to the patient can influence patient motivation and produce different ways of acting and different performances. The Intrinsic Motivation Inventory (IMI) is a multidimensional measurement method designed to assess participants' subjective experience related to a target activity in laboratory experiments [10]. It consists of a multi-item questionnaire assessing the subject's interest/enjoyment, perceived competence, effort, value/usefulness, felt pressure and tension, and perceived choice while performing a given activity. The interest/enjoyment subscale is considered a self-report measure of intrinsic motivation. The perceived choice and competence concepts are regarded as a positive predictor of intrinsic motivation. The pressure/tension is theorized to be a negative predictor of intrinsic motivation. Past research suggests that order effects of item presentation appear to be negligible. Furthermore, the inclusion or exclusion of specific subscales appears to have no impact on the others [11]. The full version of the questionnaire includes 45 items and 7 subscales; shorter versions have been used and appear to be reliable.
All patients enrolled in the experimental protocols concluded their training so indicating high adherence to our experiments.
The motivation of patients involved in the HUMOUR project was evaluated by means of a 15-item questionnaire at the end of treatment. Two additional items explored the presence/absence of pain. The pain subscale was obtained by averaging the scores of the two items. Thus six dependent variables were obtained from the 17 items.
Table 2 reports the mean values and standard deviations for five pre-selected subscales of the IMI questionnaire and pain subscale, evaluated in 13 patients enrolled in different protocols (4 in the Humour Architecture test, 5 in the PTR algorithm test, 4 in the Assist as needed algorithm test). The interest/enjoyment subscale, i.e. a self-report measure of intrinsic motivation, obtained a high score and a low standard deviation. This suggest that our patients found the robot therapy very interesting.
The perceived competence subscale resulted in a mid score (subscale value= 3.62). This result is not surprising in view of the different levels of disability of our patients. In fact, less compromised patients should obtain a better performance, and therefore consider themselves more competent in executing the exercise than more compromised patients. Also the effort/importance and value/usefulness subscales obtained a high score and very low standard deviation so indicating that patients were highly motivated in the execution of this type of treatment, and were satisfied with the results obtained. The pressure/tension subscale obtained a mid score with a high standard deviation. This means that some patients did not experience tension during training with the robot device but that other patients did. The low value of the pain subscale means that most of

our patients did not experience pain during training. The limited number of patients of each subgroup/protocol does not allow comparisons between groups of subjects.

Table 2. *Subscale findings of the Intrinsic Motivation Inventory (IMI) questionnaire evaluated in 13 patients enrolled in different protocols of the HUMOUR project (subscale range = 1 – 7).*

IMI subscale	Score (Mean±SD)
Interest/Enjoyment	5.26±1.27
Perceived Competence	3.82±1.27
Effort/Importance	5.90±1.23
Value/Usefulness	5.44±1.41
Pressure/Tension	3.03±1.71
Pain	1.54±1.17

6 Rehabilitation experiments in collaboration with Imperial College (Imperial, FSM)

A recent study [12]suggests that spatial abnormalities during movements of chronic post-stroke patients with hemiparesis are due to an impaired feedforward control rather than weakness, spasticity, or stereotypic muscle activation patterns. Our recent experiments [13] demonstrate that it is possible to appropriate feedforward commands to compensate for stable dynamics without proprioceptive error to drive the adaptation by using solely visual feedback. These results suggest that appropriately designed visual feedback could allow effective neurorehabilitation strategies using simple robotic devices despite the limitations of the moving parts of such simplified devices. In the same way gravity-compensated devices are adapted to let subjects produce more or less shoulder force, visual feedback could be used to train subjects with a planar manipulandum, to correct lateral forces in a 1DOF robot (such as ARM Guide [14] or reachMAN [15]) or to avoid compensatory movements. To test this virtual learning technique, a series of experiments with post-stroke patients has been started in collaboration between Fondazione Salvatore Maugeri (Veruno, Italy) and Imperial College (London, UK). These experiments are aimed at understanding the benefits of providing consistent visual feedback in constrained environments. We hypothesise that by showing consistent visual feedback during constrained movements it is possible to promote recovery with similar results as training in an unconstrained environment. Simplifying the devices will make them safer, cheaper and more reliable.
Experimental Protocol: The experimental setup consists in having three groups of chronic stroke, patients. In addition to conventional therapy, Group I (control) performs reaching sessions in free space using the robotic manipulandum, Braccio di Ferro; Group II (experimental group 1) performs reaching sessions constrained in a haptic channel; Group III (experimental group 2) performs reaching sessions constrained in a haptic channel, but their cursor correspond to free space movements – virtual movements (as described in [13]). Movements are trained in the forward direction only. After each movement, the patient is asked to relax so the robot could bring his arm back to the origin. Movements have to be completed between 0.5 s and 1 s. If after 3 s the patient is not able to complete the movement, the robot will bring his arm back to the origin. If the movement is between 0 s and 0.5 s, the target turns red; if it is between 0.5 s and 1 s, the target turns green; if it is between 1 s and 3 s, the target turns blue. Patients first complete two free movements per direction to familiarise with the robot dynamics (familiarisation). Then, they perform another series of five free movements per direction and those are considered as baseline (baseline).

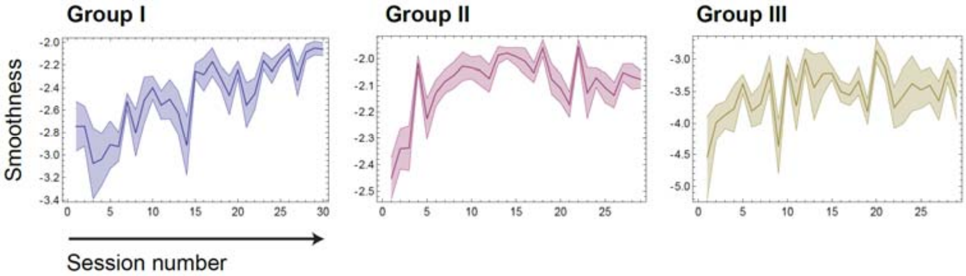


Figure 3 Spectral Arc Length smoothness metric calculated at the end of each session (free movements).

After, patients complete 37 minutes of reaching movement exercises. Group I performs free movements, Group II laterally constrained movements, and Group II virtual movements (training).The training phase starts by 5’ of movements followed by 3’of rest (8’ block), then followed by three more 8min-block and ending with another 5’ of movements (37’ in total).Finally, they perform another series of five free movements per direction and those are considered as evaluation (testing).

Preliminary results shows that all patients improved their reaching capabilities in all trained directions. In particular the spectral arc length smoothness metric [16] measured at the end of each session (figure 3) clearly improved during the course of the 30 therapy sessions. Though these preliminary experiments provide us with only little data, not enough to make conclusive statements, the performance of the patients give us motives to purse this study.

7 Improving ROM of Wrist Movements in Stroke Patients by means of a Haptic Wrist Robot (IIT)

Over the last two decades robotic rehabilitation of the upper limb in neurological patients has mainly focused on proximal movements of the arm. Few clinical studies have addressed the recovery of motor function of distal parts such as wrist. We present a preliminary study with a wrist robot aimed at improving the RoM (Range of Motion) of the wrist movements along the three anatomical axes.

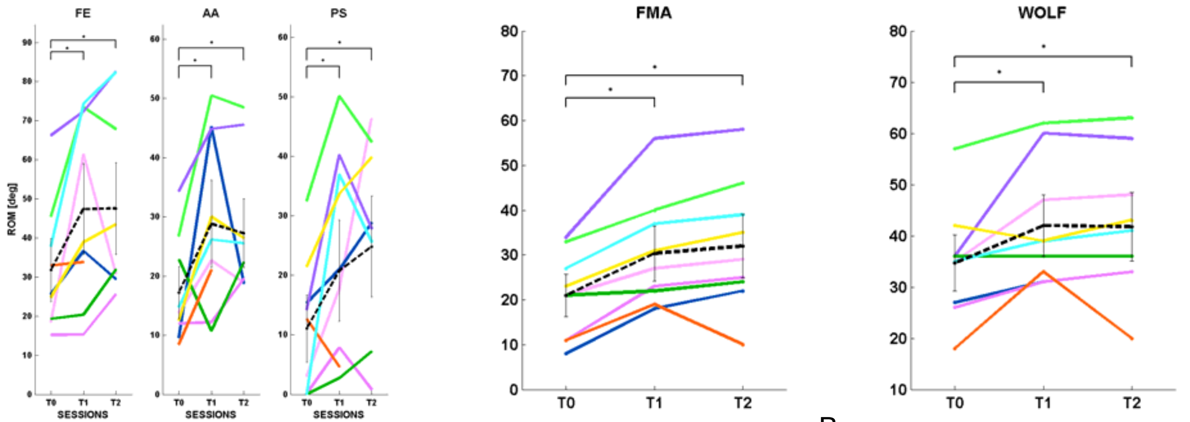
Nine chronic stroke patients participated in this preliminary study. The experimental setup consisted of a wrist robotic exoskeleton with 3 degrees of freedom (DoF) mounted on top of a planar 2 DoF manipulandum. The experimental protocol was divided into two phases:

1. Test phase: At the beginning and end of a single session, subjects were requested to freely (motors are disactivated) move one DoF at a time in order to evaluate the active voluntary Range of Motion before (ROMpre) and after (ROMpost) a single session

2. Training phase: The assistive protocol trained 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). The robotic device delivered a force field that assisted the subjects to execute the movements. In order to avoid compensation effects, the non active DoFs were kept fixed in the canonical position.

Data analysis was focused on the active voluntary ROM for each DoF and on the clinical scales (FMA and WOLF), estimated at the beginning (T0), at the end of the training (T1) and after three months (follow up, T2).

The analysis showed great improvement in the ROM for all the degrees of freedom, that



A B C

Figure 4. A. ROM measured for the three DoF. B. FMA score. C. WOLF Motor Function Test. In all the panels, colors represent different subjects. The black dotted line shows the mean and the standard error for each time of assessment. The horizontal black lines and their connected star show statistical significant comparisons (paired, two tailed ttest; $p<0.05$).

was maintained over the three months follow up (figure 4.A). Also the clinical scales showed significant improvements, maintained in the follow up assessment. In fact the FMA score (figure 4.B) highlighted a reduction of upper extremity motor impairments while the WOLF motor function test (figure 4.C) showed an improved functional use of the upper limb.

The results of our study show the feasibility of a robot-assisted therapy for the wrist joint with stroke patients. Moreover the observed improvements of the free movements of the wrist highlighted the efficacy of the exercise. The improvements in the clinical scales are of particularly note because they involve also proximal movements that were not explicitly involved in the training protocol and moreover they highlight functional improvements after the robot training.

Squeri V, Masia L, Taverna L, and Morasso P. Improving the ROM of Wrist Movements in Stroke Patients by means of a Haptic Wrist Robot. *In: 33rd Annual International IEEE EMBS Conference. Aug 30- Sep 3, 2010, Boston, MA, USA: 2011.*

Squeri V, Masia L, Giannoni P and Morasso P. Improving the ROM of Wrist Movements in Stroke Patients by means of a Haptic Wrist Robot *(In preparation).*

8 Results with BCI in stroke (EKU)

Incidence of a first stroke in Europe is about 1.1 million and prevalence about 6 million per year. Currently, about 75% of people affected by a stroke survive one year or more and this proportion will increase in the coming years due to enhanced quality in hyper-acute, follow-up acute and sub-acute care, and life-long treatment of these conditions. From all the stroke survivors showing no active upper limb motion at hospital admission, 14% showed complete recovery, while 30% showed partial recovery and 56% showed no recovery. Stroke survivors with chronic hand plegia and very low score in the Fugl-Meyer scale show limited residual muscle activity in the upper arm extensor muscles and normally no residual finger extension. Currently, there is no accepted and efficient rehabilitation strategy available that aims at reducing focal impairments in patients with chronic stroke and complete hand paralysis. In tight collaboration, the University of Tubingen (Germany) and the National Institutes of Health (NIH) demonstrated for the first time that stroke patients with complete hand paralysis can learn to control a magnetoencephalography (MEG) based Brain-Computer Interface (BCI) to drive a hand robotic orthosis (Buch et al. 2008). The BCI was used to move a cursor on a screen and depending on correct or incorrect response the hand orthotic device would or would not move the hand respectively. The results could not be translated out of the lab and patients needed the orthosis to move their hands. In a later study, we demonstrated that the combination of BCI and daily life-oriented physiotherapy can elicit functional recovery improving hand and arm movements as well as gait (Broetz et al. 2009). Furthermore, using a multimodal neuroimaging approach based on fMRI and diffusion tensor imaging (DTI) we investigated brain plasticity in the motor system along with longitudinal clinical assessments. We found a convergent association between functional and structural data in the ipsilesional premotor areas (Caria et al. 2011). Parallel to these findings we studied the effect of haptic feedback during the use of a sensorimotor rhythm (SMR) BCI. Here, an online EEG-based proprioceptive BCI was used for stroke rehabilitation (Ramos-Murguialday et al. 2009 & 2010) controlling a robotic exoskeleton online (250msec delay) using brain signals. In our study 36 chronic stroke patients with minimal residual hand extension underwent a 6-week daily online haptic-BCI rehabilitation therapy combined with goal-oriented physiotherapy. Several multimodal pre- and post-measurements were used to assess physiological and functional rehabilitation. The pre-measurements were conducted twice, two months before and immediately before the 6-week daily training. These two measurements allowed us to have a baseline of neurophysiological and psychophysiological data to check for stability and reliability of our measurements. The post-measurements were divided in two phases as well having one on the day after the last day of training and the second one six months later as a follow-up measurement. Magnetoencephalography (MEG) was used to measure sensory inputs using pneumatic vibrotactile actuators fixed to the index and pinky fingers and the lip. The ability to imagine and perform movement was assessed through a three-class protocol using MEG and functional magnetic resonance (fMRI). The MRI-scanner was also used to acquire important information related to anatomy and anatomical connectivity. To explore the corticospinal tract integrity, neuronavigated TMS was applied to the patients acquiring MEPs from lower and upper arm muscles and thus allowing us to have a more precise cortical map of flexors and extensors. TMS was applied following several protocols to elicit more stable and greater MEPs using pre contraction or imagination of movement.

Several movements included in the Fugl-Meyer scale were used to generate a protocol to register muscle activity from the healthy and paretic side for further comparisons. EEG screenings were performed in order to identify most relevant oscillatory brain frequencies and electrode positions during hand opening and closing. This information was used to set up the online proprioceptive BCI classifier. Other psychological and physiotherapeutical tests (e.g. Wolf Motor Function Test, Fugl-Meyer Score, Ashworth Scale, SEIQL) were performed to correlate functional scales with neurophysiological data. Patients were assigned into one of three different feedback contingency groups (positive, negative and non-contingent feedback). Pilot results of this clinical study will be presented and discussed.

For specific details see Deliverable 5.4 and the following papers

Broetz, D., Braun, C., Weber, C., Soekadar, SR., Caria, A., Birbaumer, N. (2010). Combination of brain-computer interface training and goal-directed physical therapy in chronic stroke: a case report. *Neurorehabil Neural Repair. 24(7): 674-679.*

Caria A, Weber C, Brötz D, Ramos A, Ticini LF, Gharabaghi A, Braun C, Birbaumer N. Chronic stroke recovery after combined BCI training and physiotherapy: A case report. *Psychophysiology 2010, 578-582.*

Ramos-Murguialday, A., Halder, S. and Birbaumer, N. (2009) Propioceptive Feedback in BCI. *In proceedings of NER'09, 4th International IEEE EMBS Conference on Neural Engineering, Antalya, Turkey, 2009.*

Ramos-Murguialday, A., Soares, E. and Birbaumer N. (2010) Upper Limb EMG Artefact Rejection in Motor Sensitive BCIs*; Engineering in Medicine and Biology Society (EMBC) Proceedings, 2010 Annual International Conference of the IEEE 2010 (1:6).*

Ramos-Murguialday, A., Caria, A., Broetz, D., Läer, L., Soekadar, S.R., and Birbaumer N. Haptic Brain Computer Interface in Paralyzed Chronic Stroke Patients. BC11 : *Computational Neuroscience & Neurotechnology Bernstein Conference & Neurex Annual Meeting 2011, Freiburg, Germany, 4 Oct - 6 Oct, 2011.*

9 Discussion and Conclusions

The work presented in this deliverable show that we observed in our patients the existence of a recovery strategy consisting of concurrent optimization processes such as goal achievement, effort optimization and movement speed improvement, each having a different dynamic evolution as demonstrated by the different time constants; the former faster and the latter slower. This recovery strategy was used to choose the set of parameters estimating patients' performance to be included in a specific algorithm to regulate training by selecting the task and assistance that is most suitable for the patient's current ability, based on the performance obtained. In addition the recovery strategy was used to design the set of rules to identify the top/bottom level of adaptation in the parameters (steady performance) to optimize training.
The findings show good agreement with the therapist decisions so indicating that the developed algorithm could be useful for the implementation of training protocols allowing individualized and gradual treatment of upper limb disabilities in patients after stroke. The application of the PTR and Assist-as-needed algorithms during robot-assisted therapy should allow an easier management of the different motor tasks administered during training thereby facilitating the therapist's activity in the treatment of different pathologic conditions of the neuromuscular system. All patients enrolled in

the experimental protocols showed high adherence and motivation during the experiments. The study assessing the effectiveness of the 3DoF wrist device is preliminary to future lines of research extending the concepts introduced and tested in the HUMOUR project to robotic devices with a higher number of DoF (wrist/arm devices) and allowing the training in 3D workspace. In this case the metrics used for performance evaluation and also the remarks about the recovery strategy adopted by patients could be different.

10 References

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