The Robot that Learns from the Therapist How to Assist Stroke Patients

M. D. Kostić, M. D. Popović and D. B. Popović

Abstract Results from clinical studies suggest that assisted training is beneficial for the recovery of functioning in patients with stroke and other central nervous system injuries. The training consists of the repetition of movements, which change the excitability of the brain, and due to cortical plasticity have carry-over effects. We are developing a 3D arm assistant that interfaces the patient at the hand/wrist. The development addresses three major issues: (1) the selection of the tasks that are appropriate for the training based on the level of motor abilities (2) the design of the visual feedback that enhances the motivation to train, and (3) the assessment of the performance. Therefore, our design integrates the new 3D robot assistant, various gaming based visual feedback, and software that acquires data on-line from sensors (position of the hand and force between the robot and the hand). The major novelties that the 3D arm assistant brings are the following: an automatic method of capturing movements presented by the therapist (expert), the use of the probabilistic movement representation for control of the robot, the incorporation of simple gaming with adjustable levels of difficulty, and finally, the assessment of differences between the achieved and target movements (kinematics) and interface force measured by a special handle with multiple sensors. The components of the new arm assistant in 2D have been tested and proved to work effectively in the clinical trials with stroke patients.

Keywords Stroke · Upper extremities · Rehabilitation · Robot assistance · Motivation · Gaming · Assessment

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1 Introduction

The rising number of stroke patients with upper limb impairment and the development of new technologies influence the efforts to improve the recovery process of patients. There is evidence suggesting that the damaged motor system can be reorganized as a consequence of motor practice. Even though optimal training methodology is unclear, there is firm evidence suggesting that quantity of training is positively correlated with recovery (Kwakkel 2009). Personal robots have been identified as a possible way to automate and assist therapists in long training sessions. Hogan at MIT (1992) was among the first to exploit the idea of assisting stroke neurorehabilitation using dedicated robotic systems. This idea and the results obtained, influenced the development of several robot assistants [e.g., Bracio di Ferro (Casadio et al. 2006), ARMin (Nef and Riener 2005), Haptic-Master (Van der Linde et al. 2002)].

One of the challenges for the robot-assisted therapy is the selection of the appropriate tasks and translation of therapist skills into the control of a robot. Several control strategies have been proposed: assistance-based, challenge-based, haptic simulation, etc. The clinical evidence regarding the relative effectiveness of a specific control method is still limited (Marchal-Crespo and Reinkensmeyer 2009). It also became known that there are mechanisms by which some robotic control approaches might actually slow down the recovery when compared with conventional forms of training (Kahn et al. 2006; Kostić et al. 2011).

We need to emphasize that robot assistants aim to be an additional tool available to the physiotherapist and not their replacement. In this context, the physiotherapist would be making all the clinical decisions and when suitable, consider the use of the robot assistant (Loureiro et al. 2011).

The basics of our research can be formulated as follows: The robot assistant should be used to facilitate and speed up the acquisition of novel motor skills of patients with diminished motor control of upper limbs. We combined behavioral studies on motor learning with the design and implementation of robot assistants that behave as "therapists", capable of efficiently exploiting the adaptive properties of the human sensorimotor system and its structures. Regarding the behavioral studies, we focused on the cognitive and neural mechanisms underlying the acquisition of a variety of motor skills that involves the upper limb. In particular, we investigated the physical interaction strategies a human uses to assist the physical training of another human. To maximize the efficiency of the learning process in terms of its specified target outcome, the robot trainer needs to be capable of continuously regulating assistance in terms of the observed performance and of the neural and cognitive correlates of adaptation.

Several ideas that influenced this research follow the findings of the HUMOUR and MIMICS project where the use of robot assistant (Bracio di Ferro and Haptic Master, respectively) was combined with the challenging feedback presented in virtual reality (http://www.mimics.ethz.ch/index.php?page_id=10) (Kostić et al. 2011; Luttgen and Heuer 2012). In the MIMICS project, the three scenarios

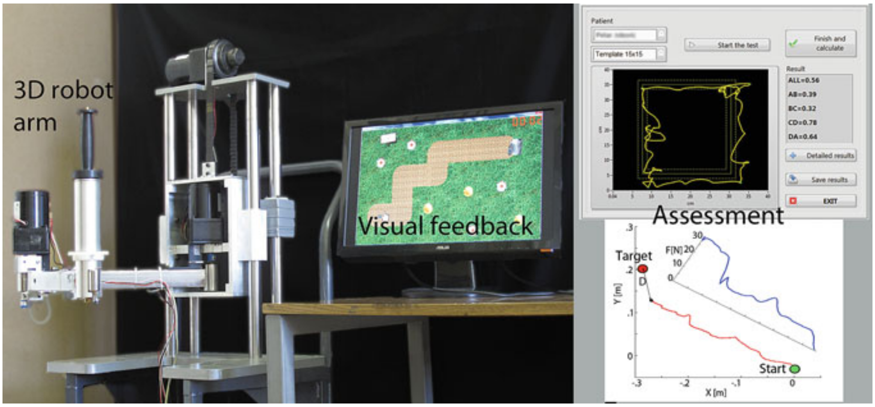

Fig. 1 The new 3D robot assistant (*left* panel) that mimics therapist assistance, visual feedback provided to the patient during the exercise allowing the adjusting of the level of difficulty of the task (*middle*), and two (out of several) measures of the quality of performance

combining motor and cognitive tasks of increasing complexity were compared (http://www.mimics.ethz.ch/index.php?page_id=10). The results indicate that the task during the exercise needs to be graded and to match the abilities of the patient. In short, the key for the success of learning from repetitions can be summarized: the task must be demanding but achievable, and the learning strategy should be from simple to complex. In the HUMOUR project, the question of defining the desired task was addressed from the perspective of motor knowledge transfer. Using research of robot aided motor learning (Došen et al. 2010; Luttgen and Heuer 2012) and human robot interaction (Zenzeri et al. 2011), a novel method for arm movement representation was defined (Kostić et al. 2013).

2 The 3D Robot: Training, Gaming and Assessment Tool

The robot that we are developing integrates a two-segment planar arm mounted on a vertical slider (Fig. 1). The joints of the planar arm were named shoulder (S) and elbow (E). The joints are instrumented with Hall-effect transducers and powered by 25 W asynchronous motors with the planetary gears (1:120 ratio). The motors can be decoupled and then the system operates in passive mode with low friction and inertia (Kostić et al. 2011). The handle (Fig. 1) comprises an in-house designed multi sensor system that measures the direction and amount of interaction force between the patient and the robot. All sensors data are acquired by NI USB-6009 DAQ. The software is developed using LabVIEW 2011. The sampling frequency for acquisition and control is 50 per second. The software integrates signal processing, control and communication in real time.

The feedback is provided by a PC based video game. The feedback shows the task and the actual movement, and shows the quality of movement measured by time and precision. The level of difficulty of the task is being automatically increased if the performance is good enough. The task and level of difficulty are always controlled by the therapist. The gaming that we developed includes also Wii Nintendo games described in detail elsewhere (Prodanović et al. 2012).

Right panels show two out of several screens relevant for the assessment, which are presented to the therapist and patient. The top one is a result of the modified drawing test (Kostić and Popović 2013) in which the ability to track sides of the square is estimated, while the bottom right panel shows the path of the hand and interface force with respect to the target trajectory.

2.1 Setup of the Training Scenario

The training scenario for the robot assistance is a replica of a conventional training provided by the therapist. This approach starts from the assumption that the experience and heuristics of an experienced physical/occupational therapist in managing the training of patients is near optimal. In a conventional training session, the therapist selects the appropriate movement based on the complete neurological status, clinical scores [Fugl-Meyer et al. (1974); ARAT (Van der Lee et al. 2001); Ashworth score (Pandyan et al. 1999)] of the patient, and experience. The therapist instructs the patient by guiding her/his paretic extremity along the target trajectory. Afterwards, the patient exercises this movement through numerous repetitions, while the therapist provides the assistance, again by leading the hand along the target trajectory. The robot assistant is anticipated as a replacement of the therapist from the tedious work. The use of the robot trainer should disturb neither the training protocol, nor the relationship between the patient and the therapist (Riener et al. 2005).

Therefore, the method that we developed follows the same training setup, and maintains the therapist as the dominant figure. It comprises the initial phase in which the therapist demonstrates the movement, and the training phase, where the patient receives assistance, but here the manual work is performed by the robot, leaving the therapist free to concentrate on patients.

During the “teaching the robot” phase, a therapist holds the top part of the handle mounted at the end point of the robot assistant, while the patient is holding (the hand could be attached to the handle if she/he is unable to grasp) the bottom part of the same handle (Fig. 2, left panel), which is instrumented with the force sensor. The therapist repeats the point-to-point movement in the horizontal plane (or in space—3D), while the patient is asked to contribute to the motion (or at least not to oppose it). The number of these repetitions is set to 15, which is sufficient for action representation used here, as we have shown in our earlier studies (Kostić and Popović 2011). The therapist selects the directions and distances in which the patient is provided assistance, based on the visual feedback on the screen.

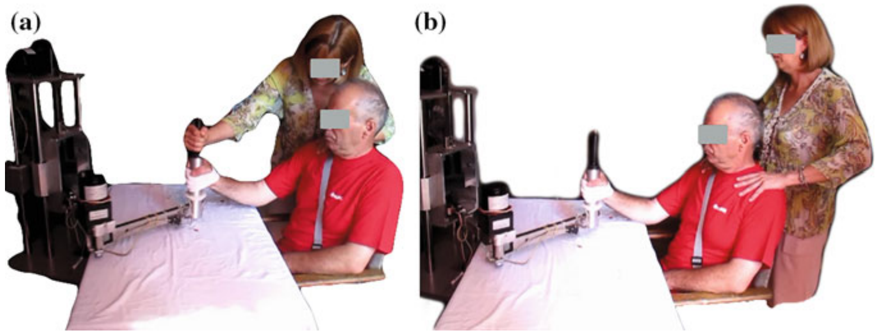

Fig. 2 *Phase A* the "teaching the robot" phase (therapist leads the movement of the robot). The selection of the target trajectory is based on feedback from the patient who holds the same handle. *Phase B* the "training the patient" phase in which robot provides assistance to the patient. The task given to the patient is to follow the trajectory shown on the screen (created during "teaching the robot" phase), while the robot assists only if the patient is unable to perform the task. The maximum assisting force is predefined to assure safety and comfort to the patient

The software allows that even short movements result with the ability to play the game. The trajectories are estimated from the Hall-effect sensors in the joints of the robot (sampling rate 100 per second, resolution of 0.01 rad). This data is filtered with no phase leg in real time and used for the synthesis of the target trajectory (Probability Tube action representation) used for closed-loop control (Kostić et al. 2013).

During the "training the patient" phase (Fig. 2, right panel), the patient is asked to move the hand in a manner to follow the trajectory shown on the feedback screen. The feedback is presented as a video game, which implements movements from the previous phase, and has positive impact on patient motivation, as shown in Popović et al. (2013). The robot is assisting this movement if the patient is not able to do so in a desired manner. The maximum assistance force is preset and limited for safety and comfort reasons (Kostić et al. 2013). The assistance force is acquired and presented on a separate screen to provide the quantified measure of the patient's contribution to the movement. If the interface force is low, then the patient is capable of executing the movement without assistance. This is the cue for the therapist to set a more demanding task. The therapist can readjust setup on-line without interrupting the training session. The detailed description of the methods to acquire data and generate the target points, trajectory and probability tube, are described elsewhere (Kostić et al. 2013; Kostić and Popović 2011).

2.2 Setup of the Games

The research results that indicate patient motivation as highly important for therapeutic outcome were the reason for integrating gaming into the robot-training scenario (Maclean and Pound 2000). Motivation is a multifaceted concept linked

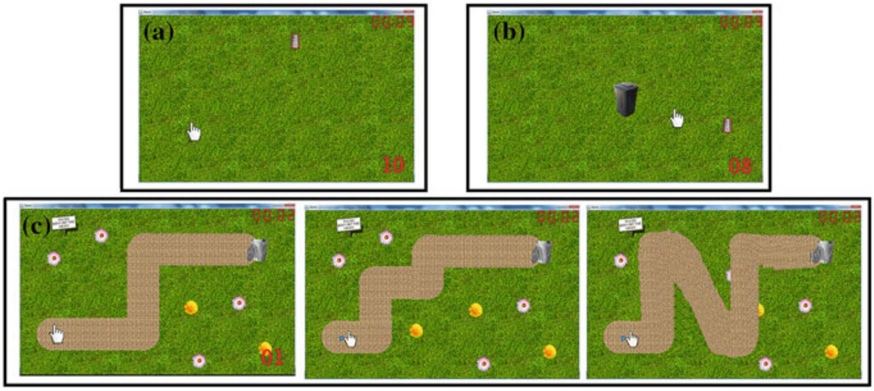

Fig. 3 The screens shown to the subject as tasks to be achieved. The complexity rises from **a** to **c**. The measure of success is the precision of the point-to-point movement/tracking and time to execute the task. The movement is continuously monitored in order to provide quantitative and qualitative measures to the clinician about the outcome of the training and for the introduction of changes of the level of difficulty to be appropriate to motor output

to several factors, including features inherent to the prescribed regimen, as well as personality traits of the patient, physician and therapist, and characteristics of the broader social environment (Maclean et al. 2002). Patients, who are highly motivated, in contrast to those who believe the outcomes of therapy depend on fate and the health system, restore their functioning to a larger extent (Campbell et al. 2001). Video games have long been known to be engaging to play; hence, developing rehabilitation games that can create a similar degree of interest can be highly beneficial for therapeutic outcome.

We are developing a feedback-mediated treatment, which uses gaming scenarios and allows on-line and off-line monitoring of both temporal and spatial characteristics of planar movements (Kostić et al. 2012). This treatment is a movement exercise, with visual feedback coming from the screen, showing targets and pathways to be followed. The targets and pathways are interactively set, as described earlier, to correspond to the abilities of the patient at any time during the treatment. The software and the user interface allow the setting of the level of difficulty of the task to be progressively increased, based on the success achieved in the game.

The gaming that we are describing here includes three types of exercises (Fig. 3) that required the activity of the proximal joints (shoulder and elbow) of the affected arm. Patients hold the handle as shown in Fig. 2 and move it in order to perform the task. Each game exercise lasts for about five minutes. This interval was heuristically found to correspond to the periods of increased motivation of the patents. However, patients can decide to stop after a shorter interval for any reason. Resting must be integrated into the training, and resting periods should be approximately as long as the actual training.

The coordinates of the end point of the robotic arm (handle) control the game. The position of the cursor on the screen shown to the patient corresponds to the position of the handle. The software allows amplification of the range of movement to allow patients with major disability to also participate in the training. The gain of amplification is decreased in parallel to the gain in functioning of the patient.

The first game (exercise) requires moving the cursor to reach targets, which are appearing in pseudo random positions on the screen (Fig. 3a). When the cursor would meet the target, it would disappear from the screen and trigger the "cash register" sound. This is followed by appearance of the next target in a pseudo random position on the screen. The minimal distance between two subsequent targets is defined to match the patient's workspace. The distance between targets gradually increases during the course of the game.

The second game (Fig. 3b) requires from patients to move the cursor to a given target, and then return to the initial position in order to trigger the next target appearance). The initial position is in the center of the workspace, and the targets are appearing in the same manner as in the first game.

In the third game, patients are presented with a target trajectory (path) which they had to follow with the cursor (Fig. 3c). Upon completion of one path, a new, more difficult path would appear. The shape and complexity of paths (varying from wide and straight paths, to narrow and complex paths) was designed by experienced therapists to match the abilities of patients.

The score (achieved speed and precision) is displayed during the game to allow patients to follow their performance. A high-score list, where patients could compare their performance to previous days and to performance of other patients, was shown after each session.

In the procedure of the development, the gaming was tested in 20 stroke patients with the 2D passive robot (Popović et al. 2013). The outcome measures were assessed from: (1) the modified drawing test—mDT; (2) received therapy time—RTT; and (3) Intrinsic Motivation Inventory—IMI. The overall conclusion is that gaming is beneficial, but that it must be tuned to match patient abilities; otherwise, it could be counterproductive.

2.3 Control of the Robot Trainer

We applied two single-input single-output Modified Internal Model Control (MIMC) liner digital controllers (Matausšek et al. 2002) to control the proximal (shoulder) and the distal (elbow) joint of the system robotic arm. Simple models G_{mpE}(s) of the elbow position p_E(t) [rad] and G_{mpS}(s) of the shoulder position p_S(t)

[rad] are developed from open-loop step response tests. Model G_{mpE}(s) is defined by the following transfer function:

$$G_{mpE}(s) = \frac{K_E e^{-L_e s}}{s(T_E^2 s^2 + 2\zeta_E T_E s + 1)},\quad K_E = 2.4 \times 10^{-4},\ L_E = 0.07,\ T_E = 0.04,\ \zeta_E = 0.7. \tag{1}$$

Model G_{mpS}(s) is defined by

$$G_{mpS}(s) = \frac{K_S e^{-L_S s}}{s(T_S^2 s^2 + 2\zeta_S T_S s + 1)},\quad K_S = 2.3 \times 10^{-4},\ L_S = 0.1,\ T_S = 0.08,\ \zeta_S = 0.7. \tag{2}$$

The controlled variables consist of the velocity of the elbow and the velocity of the shoulder. However, the measured variables on the patient are in the elbow and shoulder positions. Therefore, velocity of elbow v_E(t) [rad/s] and velocity of shoulder v_S(t) [rad/s] are obtained as first derivative of measured variables. Their dynamic characteristics are defined by the elbow velocity model G_{mvE}(s) and the shoulder velocity model G_{mvS}(s), which are obtained from (1) and (2). Model G_{mvE}(s) is defined by

$$G_{mvE}(s) = \frac{K_E e^{-L_E s}}{T_E^2 s^2 + 2\zeta_E T_E s + 1}. \tag{3}$$

Whereas model G_{mvS}(s) is defined by

$$G_{mvS}(s) = \frac{K_S e^{-L_S s}}{T_S^2 s^2 + 2\zeta_S T_S s + 1}. \tag{4}$$

The applied MIMC controller for elbow C_E and shoulder C_S can be derived from (1)–(4), as

$$C_E(s) = \frac{G_{mvE}^{-1}(s)F(s)}{1 - F(s)e^{-L_E s}}, \tag{5}$$

$$C_S(s) = \frac{G_{mvS}^{-1}(s)F(s)}{1 - F(s)e^{-L_S s}}, \tag{6}$$

where F(s) is a second order filter applied on error measurement. Detailed description of the control can be found in Kostić et al. (2013).

2.4 Assessment Provided by the Robot

The International Classification of Functioning, Disability and Health (ICF) relates to two domains: a list of body functions and structures, and a list of activities in daily life and social participation. The efforts of the European Experts group within the COST project TD 1006 (http://www.rehabilitationrobotics.eu/), created the lists with three categories: (1) capability measures, (2) pathophysiological measures, and (3) task performance measures.

The capability measures characterize the capacities such as range of motion (active/passive), overall workspace, maximum strength under isometric conditions, maximum joint power (non-isometric), and proprioception. The system that we developed allows the assessment of the range of motion and maximum strength under isometric conditions.

The pathophysiological measures quantify different impairments seen in neurological disorders such as abnormal synergies, spasticity, rigidity, ataxia, movement and postural asymmetries, and pain occurring or induced by the movement. The system that we developed allows the assessment of the abnormal synergies and spasticity.

The task performance measures quantify how well a task has been executed, including measures such as: execution time to complete a specific task, success rate of accomplishing the task, disturbance recovery, quality of movement for a specific task (smoothness, speed-accuracy curve, number and kind of unwanted collisions with objects, repeatability), and several measures related to grasping. The system that we developed allows the assessment of the execution time, smoothness, number of collisions, and speed-accuracy curve.

We present here one of the assessments that is facilitated with the 3D robot that we developed (Kostić and Popović 2013). The testing procedure comprised drawing a square based on the presented template, a 2-cm wide rectangular path. The path is formed by two concentric squares, with the side difference of 4 cm. The task is to complete the rectangular path (all four sides) as fast and precise as possible. The size of the template is determined by the initial measurement of subject's ROM.

The outcome measure of this test comprises three objective measures: movement speed, movement precision error, and movement smoothness. The average speed was calculated as the ratio of length of a single side of the square and the time used to complete that side. The precision error was calculated as the area of transgressions outside the path. Areas enclosed by the drawing and template lines outside the path were detected, counted, and measured automatically, using the image processing methods. Precision error was defined as the total area of transgressions multiplied by their number, normalized with respect to the area of the template square. Smoothness measure was defined as a function of four smoothness parameters proposed in Rohrer et al. (2002).

The entire testing procedure is supported by custom-made software with user-friendly interface (Fig. 4), which enables simple testing, and instant access to

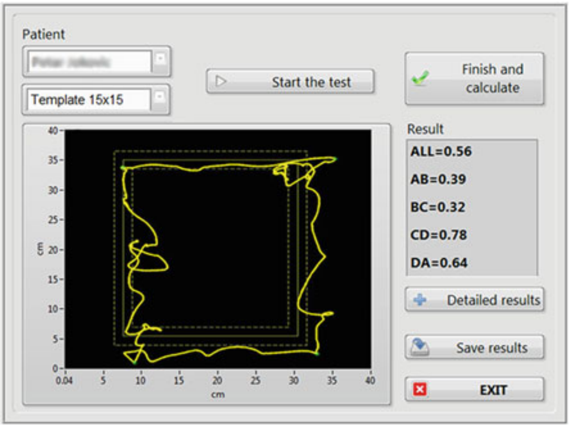

Fig. 4 User-friendly software for on-line assessment of performance. The window provides intuitive commands for the testing procedure and the score

results. In order to expedite the testing procedure, only basic commands and the score are provided in the main window, shown in Fig. 4, while detailed analysis of data can be performed by entering the advanced data analysis window. The results presented in Kostić and Popović (2013) indicate the applicability of this method in clinical assessment of patient performance.

Finally, we show here the assessment of the interface force and the "error" in reaching the target during the exercises. Figure 5 shows the setup and the processed output from the sensors. The position of the hand is being calculated from the measured joint angles, while the force is estimated based on the developed force sensor.

In the example shown in Fig. 5, it is clear that the patient was not able to follow the task and could not reach the target point (spastic patient, Ashworth grade 4). Though the robot was programmed to assist the movement in reaching the target point, for safety reasons the robot-generated force was limited to 30 N, hence the movement stopped before actually reaching the target. In the case of contralateral movement, the distance between the movement endpoint and the target was $D = 9.6$ cm, while in the ipsilateral direction the error was only $D = 2.9$ cm.

The interface force (Fig. 3, right panels) indicates that the robot was pulling the handle along the trajectory. Thus, the robot assisted the movement with strong force during the last 25 % of the actual movement ($F \approx 30$ N), whereas the force was approximately 10 N during the first 75 % of the movement. These two measures indicate the patient's ability to perform the target movement, as well as the generated force. They can be used for patient assessment, but also as feedback used by the therapist when selecting the level of difficulty for the robot-assisted rehabilitation.

The most important measure fed back to the patient is the game performance. This information is given by the time and number of repetitions within the preselected interval. This has been shown to influence patients in a highly competitive

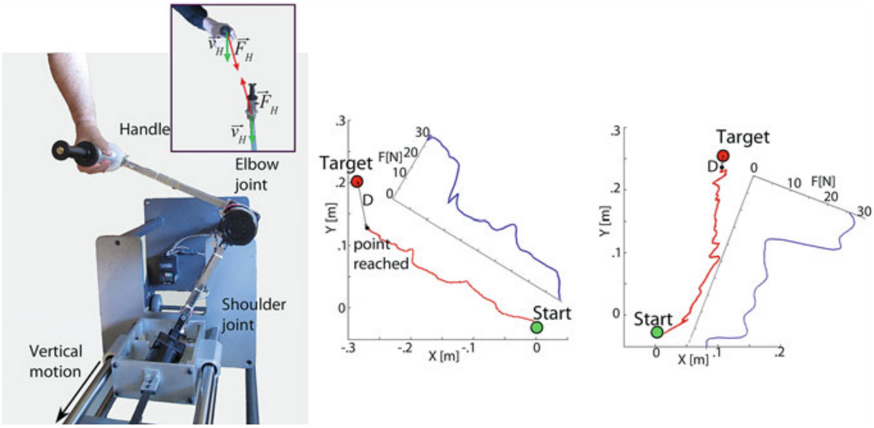

Fig. 5 The assessment of performance with the new robot assistant. The two *right* panels show the force estimated from the sensors in the handle, and the error (*D*) in reaching the target from the sensors in the robot joints. The recordings are from a patient that suffered stroke and is spastic (Ashworth grade 4). It is noticeable that the force generated by the robot (limited by controller to 30 N) is not adequate to move the spastic elbow, especially if the task was the movement from the point in front of the shoulder in the contralateral direction

manner (Popović et al. 2013). It allows patients to follow their own progress, but even more importantly, calls for competition with their peers.

3 Conclusions

We presented here the design and the methodology of use of the system in the clinical condition that could improve the rehabilitation of patients with upper extremity disability. The system that we are developing has an open architecture and allows simple integration with functional electrical stimulation systems that would control the grasping functions and possibly the hand orientation (Popović-Maneski et al. 2013). We developed earlier systems with array electrodes that allow selective activation of forearm and hand muscles, as well as the sensors system that can integrate easily into the 3D robot presented (Malešević et al. 2012).

We present the development of the 3D robot, which controls the position of the hand/arm. This could be seen as the replica of other robot assistants that control the end point trajectory. The novelties in the system presented are in control that integrates the selection of the trajectory, adaptation of the trajectory during the exercise, selection of the complexity of gaming by the therapist, and over all, the assessment features that are instrumental in judging if the training is appropriate or not. The reason why we decided to build our own robot is the necessity to have full control of all elements, having in mind that the robot assistant is to be used by clinicians without interference with the therapeutic session.

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