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Rehabilitation Robot for Unimanual and Bimanual Training of Hemiparetic Subjects

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***Abstract*—The goal of the study is the development and testing of a bimanual training system that stimulates the use of both arms of hemiparetic subjects using both bimanual and unimanual training exercises. The adaptive assistance controller adjusts the help of the unaffected arm, thus reducing the load on the paretic arm. Hemiparetic subjects performed three different tracking exercises in both bimanual mode and in two unimanual modes. In bimanual mode the patient uses the unaffected limb to initiate and guide the movement. By comparing the results of bimanual training with the unimanual performance (with paretic or unaffected limb) we can assess the affects of the bimanual training. High and significant correlation between bimanual training and unimanual performance was observed. The training resulted in improvements of motor performance.**

Keywords: bimanual rehabilitation, hemiparesis, rehabilitation robotics, upper limb rehabilitation, stroke

I. Introduction

The leading cause of disabilities among adults in developed countries is stroke and the most common motor deficit following it is hemiparesis that affects about 75 % of stroke survivors [1]. A wide range of everyday activities is bimanual and require a coordinated use of both upper extremities. Consequently, one of the suggested therapeutic techniques is bimanual training that engages both limbs simultaneously in order to encourage the interlimb coordination. It has been found to improve dexterity, grip strength and functional ability of the paretic limb [2]. It has been suggested that the contralesional (undamaged) brain hemisphere might provide a template of appropriate neural responses for a restored neural network [3].

Robotic systems as guidance and evaluation devices are being introduced in post-stroke rehabilitation. Several studies have examined the effects of robotic assistene on paretic arm function recovery in post-stroke rehabilitation [4]. Various robotic devices have been developed to promote bimanual training of upper extremities. A driving simulation called Driver's SEAT showed that bimanual steering using force cues increased the use of the affected arm throughout the bimanual steering task [5]. Another attempt is the bimanual lifting rehabilitator [6]. If the affected limb is unable to contribute to the bimanual task of lifting a cafeteria tray, the device substitutes for it. If the affected arm can accomplish the task, the rehabilitator does not intervene. On the down side, this system does not stimulate hemiplegic subjects to use their affected arm as the lifting task is always completed independently of the paretic arm effort. Some other systems use two robots for bimanual training [7], [8]. It has been shown that combined unimanual and bimanual robotic training has advantages compared to conventional therapy only [7].

Newer robotic rehabilitation systems use patient-cooperative control or "assist as needed" techniques to adapt the training to individual patients [9]. By recognizing the patient's intention and motor abilities the system adapts its robotic assistance to the activity of the patient. Online evaluation of human-robot interaction forces (torques) or positional measurements of the robot are needed to determine the patient's intentions and abilities. Bimanual training can use the limb coordination and forces of both limbs to do so. The system also informs the patient of his/her performance by displaying relevant information on a screen via virtual reality environment to increase motivation and training effectiveness. Highly motivating environments that increase task engagement are important for motor relearning and recovery after stroke [10].

Bimanual training that stimulates coordinated use of both arms can be extended with an intuitive patient-cooperative control that adapts the training to the needs and abilities of every individual patient. The paper presents the development and validation of a robot system designed in this way that combines the positive effects of both bimanual training and patient cooperative adaptive robot assistance. If a patient cannot perform the task with both arms in a coordinated way, the adaptive nature of the system increases contribution of the unaffected arm, thus reducing the effort of the paretic arm. To guide the training and increase motivation, a tracking game was developed.

II. Materials and methods

A. Experiment setup

The bimanual training system presented in this paper is based on the haptic robot HapticMaster (*FCS Control System*) [11]. The HapticMaster robot system has been proven to be appropriate for research of upper limb motor rehabilitation [12]. The existing three active degrees of freedom of the robot were expanded with an extra active joint with bimanual handlebars (see Fig. 1) mounted on it. Two 6-degree-of-freedom force and torque sensors mounted on the handelbars independently measure forces generated by each arm.

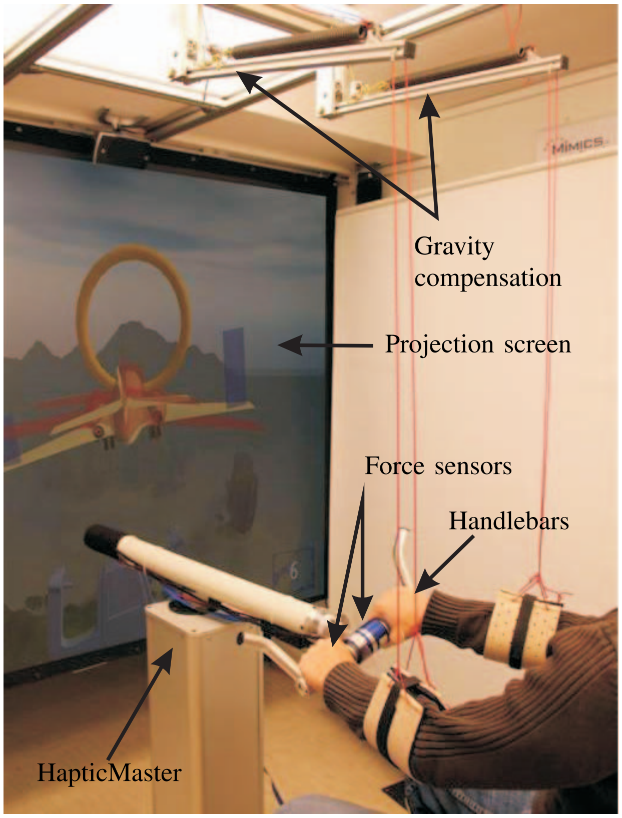

Fig. 1. Subject during training on the bimanual system.

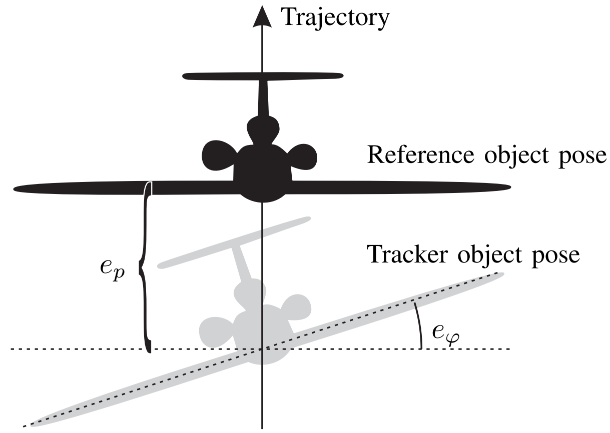

Fig. 2. Movement trajectory, reference pose, measured pose of the robot end-effector (handlebars) and tracking errors e_p and e_φ.

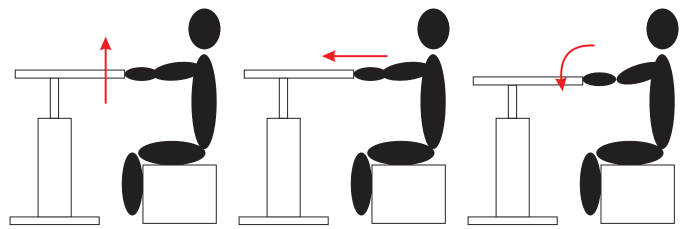

Fig. 3. Exercise types – active movement is indicated by the arrow.

The HapticMaster robot is used to constrain movement trajectories and to measure the pose of the bimanual handlebars. The robot does not actively assist the subject during training, but it provides programmable resistance to the movements (inertia, viscose friction) and can ensure the desired force ratio of both arms.

B. Training exercises

Training exercises were designed to be performed in the sagittal plane in front of the subject, predominantly in vertical or horizontal direction. A *reference object* (virtual airplane) displayed on the screen moves along a predefined trajectory. In order to simplify the task, the reference object orientation is kept constant. The subject is required to track the reference object pose by moving the robot end-effector indicated with a *tracker object* also displayed on the screen. The situation is shown in Fig. 2. The user must coordinate both arms to keep the tracker object orientation constant.

If the paretic arm is not able to perform as required (the forces applied by the paretic arm are smaller than the forces applied by the unaffected arm), the forces applied by the unaffected limb are scaled down using an adaptive gain to stimulate the use of the paretic limb. The scale factor depends on the average orientation error e_φ between the reference and the tracker object. Once the force of the unaffected arm is scaled down a higher combined effort of both arms is needed to complete the task. If the effort increases too much and the subject cannot track the reference object position, the overall combined force required to complete the task is decreased, depending on the positional tracking error e_p between the reference and the tracker object. Nonetheless, this does not change the force ratio between arms.

Three different tasks (see Fig. 3) were designed to stimulate training of different muscle groups. The robot is programmed to constrain the motion of the handlebars to the trajectory of the selected exercises (tasks):

1 *Vertical movement* – flexion of the shoulder joint with extended elbow joint,
2 *Horizontal movement* – extension of the elbow joint and protraction of the shoulder joint,
3 *Elbow extension* – isolated extension of the elbow joint, upper arms kept tight at the upper body.

Each exercise can be divided into two parts: *Stimulated movement* indicated by arrow direction in Fig. 3 and *return movement* in the opposite direction. The stimulated movements are described above and stimulate the patient to use the less active (weak) muscle groups against some resistance produced by the robot. In the opposite direction (return movement) resistance is not applied as stroke patients usually over-activate these muscle groups.

Two unimanual exercise modes were implemented as a validation method. The task requires the use of only the unaffected arm or only the paretic arm. In the unimanual mode, the rotation of the handlebars was locked to its initial horizontal orientation. A comparison of the unimanual perfomance with the unaffected and paretic arm was performed to assess effects of the bimanual training. Differently from the bimanual, the unimanual mode focuses on the positional tracking and not on the tracker object orientation. The unimanual modes enable objective measure of motor performance improvement while on the other hand, the bimanual mode was primarily intended as a training exercise.

C. Control strategies

The controller for the system was designed as a Matlab Simulink model and implemented on an xPC Target PC.

1) Adaptive assistance control: The assitance controller is designed in a way that the contribution of the unaffected arm forces on the handlebar can change, depending on the subject's performance. If the paretic (weaker) limb cannot perform as well as the unaffected (stronger) limb as is usual with hemiparetic subjects, the unaffected arm can assist with a larger contribution to the combined movement. The main control goal is that the paretic arm contributes as much as possible to tracking the reference object. If needed the forces applied by the unaffected arm are scaled down with the adaptive gain K_φ. The virtual adaptive forces used for robot control are defined as

$$F_u^* = K_\varphi F_u; \qquad F_p^* = F_p. \tag{1}$$

where F_u and F_p are measured forces of the unaffected and paretic arm, respectively, F_u^* and F_p^* are the corresponding virtual adaptive forces of the unaffected and paretic limb, respectively, and K_φ is the adaptive gain that scales the original forces to represent the subject's performance via virtual forces.

The adaptive assistance controller was implemented using a general learning law [9]. For maximum stimulation of the paretic arm the, controller gain is not only dependent on the performance of the paretic limb, but it also decreases over time towards equal contribution of both arms.

$$K_{\varphi,i+1} = (1+\mu_\varphi)K_{\varphi,i} - g_\varphi e_\varphi, \tag{2}$$

where $0.2 \leq K_\varphi \leq 1$. $K_{\varphi,i+1}$ is the adaptive gain at a discrete time step $i+1$, e_φ is the orientation error of the tracker object, μ_φ is defined as the forgetting factor and g_φ as the learning gain. Variables μ_φ and g_φ are experimentally defined gains.

The HapticMaster robot is an admittance-controlled haptic interface – the robot is controlled by applying force to its end-effector. As the system is bimanual, the virtual forces of both arms are summed to produce a control force

$$F_c = F_p^* + F_u^* = F_p + K_\varphi F_u. \tag{3}$$

With the change of K_φ, the effort required to move an admittance-type robot is increased and if it increases too much, the subject might not be able to track the position of the reference object. Thus, a positional adaptive gain K_p is introduced to compensate for this

$$K_{p,i+1} = (1-\mu_p)K_{p,i} + g_p e_p, \tag{4}$$

where $K_p \geq 1$, μ_p and g_p are experimentally defined gains, and e_p is the position error between the reference and the tracker object position. The adaptive control force, used in the robot controller, is then defined as

$$F_c^* = K_p(F_p^* + F_u^*) = K_p(F_p + K_\varphi F_u). \tag{5}$$

If e_p increases, K_p partially cancels the effect of K_φ, but it does not alter the force ratio defined by K_φ. This ensures that the combined effort of both arms does not increase if the subject is not able to perform the tracking task.

In the unimanual mode the adaptive assistance control is disabled. Both adaptive gains are constant and set to their initial values, $K_\varphi = 1$ and $K_p = 1$.

2) Robot admittance control: The adaptive control force F_c^* defined in (5) is used in the HapticMaster admittance-controller to compute the position p_r and velocity $\dot{p}_r$ of the robot end-effector using a simple second-order dynamic model

$$F_c^* = m\ddot{p}_r + b\dot{p}_r, \tag{6}$$

where m is the robot end-effector virtual mass, b is the virtual damping and p_r is the robot end-effector reference position.

3) Model of the steering wheel: To guarantee an accurate response of the bimanual handlebars a dynamic model of a steering wheel was introduced. The model describes the wheel response to forces (torques) applied by the subject as

$$\tau_{pu} = I\ddot{\varphi}_r + B\dot{\varphi}_r + K\varphi_r, \tag{7}$$

$$\tau_{pu} = r(F_r^* - F_l^*). \tag{8}$$

Variable φ_r defines the reference angle of the steering wheel measured from the horizontal orientation. The second-order model describes the wheel response via inertia (I), rotational damping (B) and stiffness (K). Stiffness is introduced to force the wheel towards the initial horizontal orientation. Variable r defines the length of the handlebar ($r = 15$ cm). Adaptive forces of the left and right arm are defined as $F_l^* = F_p^*$ and $F_r^* = F_u^*$ for left hemiparesis, and $F_l^* = F_u^*$ and $F_r^* = F_p^*$ for right hemiparesis. From (7) φ_r and $\dot{\varphi}_r$ are computed and used as reference orientations for the robot proportional-derivative orientation controller.

D. Visualization

A virtual flight simulator environment (Fig. 4) was developed to enhance subject's motivation [13]. Two jet planes are displayed on the screen in front of the subject. The transparent red jet represents the reference object with preprogrammed motion according to the exercise type and independent of the subject's actions. The second, yellow plane represents the pose of the tracker object corresponding to the pose of the bimanual handlebars. Two bars on the wings of the tracker plane are displayed, whose heights represent the forces of each arm in the direction of the desired movement. The desired flight direction is represented by targets – orange circles.

In bimanual training, subjects are instructed to follow the movements of the red reference plane with the yellow plane. The plane is required to remain horizontal – it should fly straight. This can be done by applying equal forces with both arms. In the unimanual mode the only instruction is to track

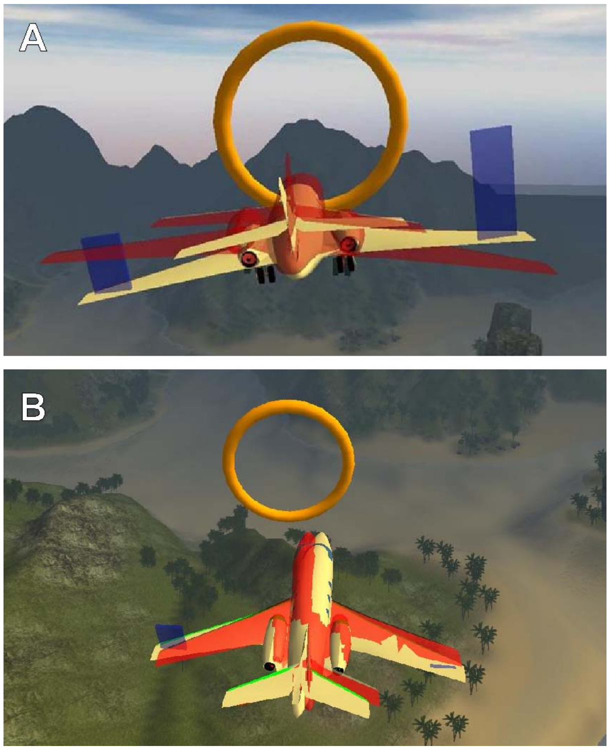

Fig. 4. Virtual flight simulator enviroment. A) Vertical movement and elbow extention; B) Horizontal movement

the position of the reference plane since the tracker plane's orientation is kept constant.

E. Experimental protocol

The participants in a pilot study were four chronic hemiparetic subjects (S1–S4). Their basic characteristics are summarized in Table I.

TABLE I
CHARACTERISTICS OF FOUR CHRONIC HEMIPARETIC SUBJECTS (S1–S4)

Patient data / Subject	S1	S2	S3	S4
Gender	female	male	female	female
Age (years)	42	50	47	45
Time since stroke (years)	11.5	6	5	13
Affected body side	right	right	left	right

To specify the level of impairment, muscle tone and upper extremity functions were assessed using Modified Modified Ashworth Scale [14] seen in Table II and Motor assessment scale for stroke [15] in Table III, respectively.

The aim of the training protocol was to facilitate activity of some commonly weak muscle groups after stroke (shoulder flexors, shoulder protractors, and elbow extensors) with minimal or no increase of activation in the overactive muscle groups including those with increased muscle tone.

Each subject performed two sessions a week for four weeks – a total of eight sessions. Each training session consisted of three exercises described earlier. The exercises were performed in a specific order: Vertical movement → Horizontal movement → Elbow extension. Each exercise was first performed

TABLE II
MUSCLE TONE BY MODIFIED MODIFIED ASHWORTH SCALE: 0 = NO INCREASE, 4 = RIGID PART; SUBJECTS S1–S4

Muscle group / Subject	S1	S2	S3	S4
Shoulder abductors	2	0	2	0
Shoulder abductors	1	0	0	0
Shoulder internal rotators	1	2	1	1
Shoulder external rotators	1	0	0	0
Elbow flexors	2	1	1	2
Elbow extensors	0	1	0	0
Wrist and fingers II.-V. flexors	2	1	0	0
Fingers II.-V. flexors	0	2	3	1
Thumb flexor	2	0	0	0

TABLE III
UPPER ARM FUNCTION BY MOTOR ASSESSMENT SCALE: 0 = PERFORMANCE NOT POSSIBLE, 6 = NORMAL SUBJECT PERFORMANCE; SUBJECTS S1–S4

Function / Subject	S1	S2	S3	S4
Upper arm function	3	1	4	6
Hand movements	0	0	3	6
Advanced hand activities	0	0	0	2

unimanually using the unaffected arm, then in the bimanual mode and finally as a unimanual exercise of the paretic arm. Ten stimulated movements were performed in each training mode. Each session lasted approximately 30 minutes.

F. Electromyography

Electromyogram (EMG) was recorded in one session for one subject (S1), to assess the muscle activation during bimanual training. EMG was recorded on four arm muscles (trapezius, deltoideus, biceps branchii and triceps branchii) on the paretic and also on the unaffected arm. EMG signals were collected at a sampling rate of 4800 Hz [16]. The EMG was filtered using a band-pass filter with cut-off frequencies of 20 Hz and 500 Hz and a 50 Hz notch filter. For representation the moving average of the signal and the average of 10 movement repetitions was computed. Signals of the same muscles on the left and the right arm were normalized to the same range using the known level of force applied by each arm.

III. RESULTS

Tracking performance was evaluated based on position tracking errors assessed during unimanual and bimanual exercises. The root-mean-square (RMS) values of positional tracking errors for different tasks in bimanual and both unimanual modes are considered. The comparison of unimanual and bimanual exercises is shown in Fig. 5. In both figures, the RMS tracking errors for the two unimanual modes and the bimanual mode by individual sessions are shown for all three exercise types. An example of less affected subjects is subject S3, whose tracking errors are shown in Fig. 5 left. Subjects S1 and S4 have similar results to that of S3. The tracking errors for all three modes follow a similar pattern. In the first session, the tracking error was relatively large. In the following sessions, the errors were smaller and constant. No major differences were observed for three exercise modes indicating that subjects were able to use also their paretic arm, which is in agreement

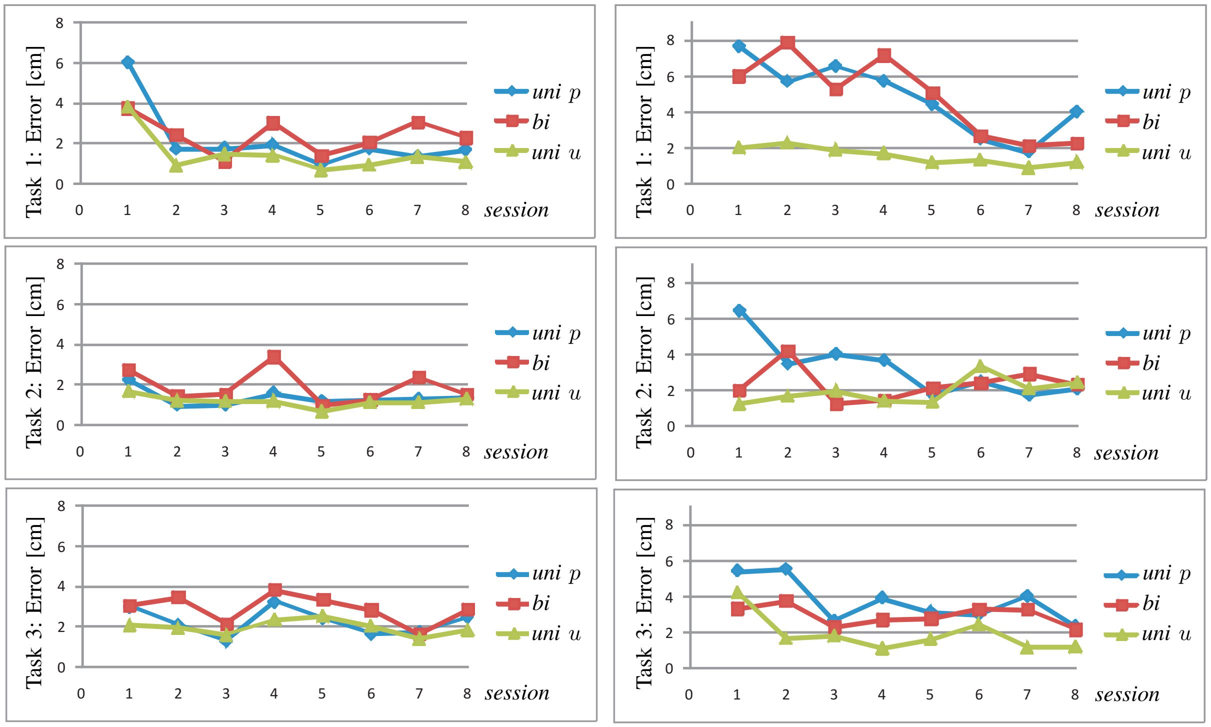

Fig. 5. RMS tracking errors for subject S3 (left) and S2 (right) by sessions; unimanual paretic arm movements (*uni p*), bimanual movements (*bi*) and unimanual unaffected arm movements (*uni u*). The x axis shows the sessions.

with their motor scores. Fig. 5 right presents the results for subject S2 that are distinguishably different from the other three subjects. A greater difference between the paretic and the unaffected arm in unimanual mode can be immediately observed. The tracking errors for bimanual mode are similar to those of unimanual mode performed with the paretic arm.

Filtered, scaled and averaged EMG signals of the deltoidus muscle of paretic and unaffected arm of the subject S1 during the unimanual and bimanual vertical movement are shown in Fig. 6A. The activation of the paretic deltoidus muscle during the unimanual and bimanual movement is very similar. During bimanual movement the activation of the unaffected deltoidus is greater than the paretic muscle. During the horizontal movement, the activation of deltoidus and trapezius muscles is stimulated. EMG signals of both deltoidus muscles are presented in Fig. 6B. The activation of the paretic and unaffected arm deltoidus muscle during the bimanual exercises are similar, but both lower compared to the unimanual mode. The EMG signals of the trapezius muscles (Fig. 6C) show that the level of activation of the paretic arm is even higher than that of the unaffected arm. No major differences can be noticed for the paretic arm during unimanual and bimanual exercises. In both figures it can be seen that the paretic arm was more activated than the unaffected arm.

IV. Discussion

The paper presents the development and proof of concept of a novel system for bimanual training in rehabilitation of stroke patients. Four hemiparetic subjects participated in the pilot study. After eight training sessions and with the teaching of correct movements by a physiotherapist the activation of the paretic arm during bimanual exercises was found to be similar to the activation during unimanual training.

The EMG data confirm the data given by the robot force and position sensors, although they were recorded for only one session. During the bimanual exercise the activation of the muscles of the paretic limb is comparable to or higher as the activation during the unimanual exercise of the paretic limb.

Previous research of connections between unimanual and bimanual training has shown that rehabilitation may be facilitated by bimanual motor practice, but is likely to require further unimanual training to maximize motor recovery [17]. In our study, the Pearson correlation between tracking performance (RMS tracking errors) for bimanual training and tracking performance for unimanual assessment of the paretic arm is statistically significant ($r = 0.71$, $p < 0.001$). This correlation factor is much higher than the correlation factor between the bimanual and unimanual tracking with the unaffected arm ($r = 0.39$, $p < 0.001$) and confirms that bimanual training might have an affect on unimanual performance. When bimanual performance improved, the unimanual performance using the paretic limb also improved significantly.

The approach to bimanual rehabilitation used in the study is different from the ones used in other robotic systems in many aspects. In contrast to some other systems where the impaired limb is passively moved by the unaffected limb, the subjects in our system must actively use both arms to complete

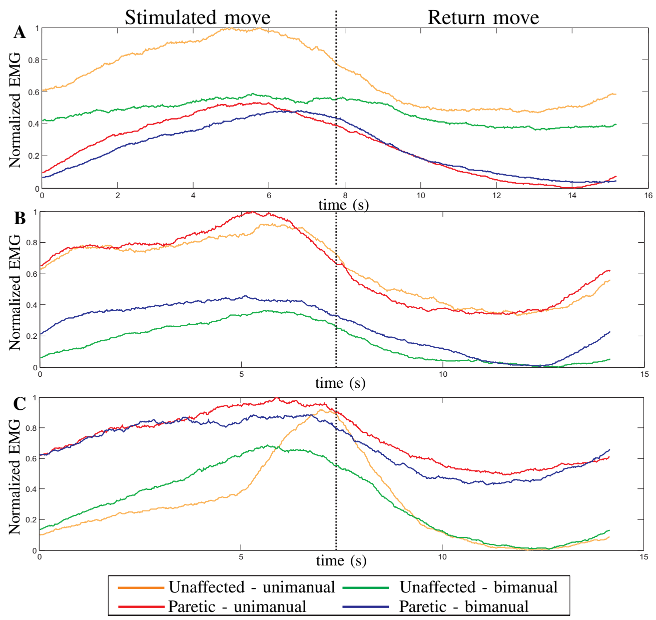

Fig. 6. A) Normalazed EMG of the deltoidus muscle during vertical movement; B) EMG of the deltoidus muscle during horizontal movement; C) trapezius muscle during horizontal movement.

the exercises. This approach is very intuitive and does not require long learning times. Furthermore, the use of only one robotic device makes the training easier and makes the design and development of the system more cost efficient and less complex compared to a multi-robot system.

V. Conclusion

The paper presents a system for unimanual and bimanual training. In bimanual mode the system encourages simultaneous and coordinated use of both arms. The training under the supervision of a physiotherapist results in improvements of motor performance. Subjects with greater impairment may benefit most from the adaptive support provided by the system.

Training improved the tracking performance of subjects participating in this study. The correlation between bimanual training and unimanual paretic arm performance proved to be high and significant.

Bimanual training has several advantages over unimanual training; during bimanual training, the subjects themselves can control the execution of the exercises and the realization of "mirror therapy" is possible. Further, the bimanual training addresses directly the problems related to patient-cooperative control of robotic systems.

A general patient-cooperative robot controller requires the robot to predict the patient's intentions. The proposed bimanual training brings the patient-cooperative control to a different level. The patient uses the unaffected limb to initiate and guide (assist) the movement. The motor activity of the paretic arm is stimulated with the applied principle to be performed in coordination with the unaffected arm.

In addition to training, the system is used as an evaluation device to monitor the patient's progress and level of motor functionality. The relative power of the paretic arm is a good indicator of the patient's abilities and can be used as an index of symmetry for clinical environments.

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