

Full paper

Rehabilitation Robot with Patient-Cooperative Control for Bimanual Training of Hemiparetic Subjects

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Abstract

Hemiparesis is the most common motor deficit following stroke. Bimanual training and robot-assisted therapy are often used to regain motor functionality of the paretic limb. The goal of this study is the development and validation of a bimanual training system that stimulates the use of both arms of hemiparetic subjects. The adaptive assistance control adjusts the contribution of the unaffected arm, thus reducing the load on the paretic arm. Hemiparetic subjects performed three different tracking exercises in bimanual mode and in two unimanual modes to validate the applicability of the system. In bimanual mode, the patient uses the unaffected limb to initiate and guide the movement. The movement of the paretic limb must be coordinated with the unaffected limb to complete the exercise. The training resulted in improvements of motor performance. High and significant correlation between bimanual training and unimanual performance was observed.

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Keywords

Bimanual rehabilitation, hemiparesis, rehabilitation robotics, upper-limb rehabilitation, stroke

1. Introduction

Stroke is the leading cause of disabilities among adults in developed countries [1]. Hemiparesis is the most common motor deficit, affecting about 75% of stroke survivors. Disabilities in the upper extremities severely limit voluntary motor control. Thus, more effective rehabilitation techniques are constantly being searched for.

Most activities of daily living are bimanual and require a coordinated use of both upper extremities. Consequently, one of the suggested therapeutic techniques is bimanual training. Bimanual training engages both limbs simultaneously in order to encourage the inter-limb coordination. It has been found to improve dexterity,

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grip strength and functional ability of the paretic limb [2, 3]. It has been suggested that the contralesional (undamaged) brain hemisphere might provide a template of appropriate neural responses for a restored neural network. Changes in the contralesional hemisphere of some patients were reported after bimanual training [4].

In recent years, the use of robotic systems as guidance and evaluation devices has been introduced in post-stroke rehabilitation. Several studies have examined the effects of robotics on paretic arm function recovery in rehabilitation of stroke patients [5–7]. Various robotic devices have been developed to promote bimanual training of the 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 [8]. Another attempt is the bimanual lifting rehabilitator [9]. 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. However, this system does not stimulate hemiplegic subjects to use their affected arm since the lifting task is always completed independently of the paretic arm effort. Some other systems use two robots for bimanual training [10, 11]. It has been shown that combined unimanual and bimanual robotic training has advantages compared to conventional therapy only [10].

Newer robotic systems in rehabilitation use patient-cooperative control or 'assist-as-needed' techniques to adapt the training to individual patients [12, 13]. These types of control take the patient's intentions and voluntary efforts into account rather than imposing any predefined movements. By recognizing the patient's intention and motor abilities, the system adapts its robotic assistance to the activity of the patient. The system also informs the patient of his/her performance by displaying relevant information on a screen. Online evaluation of human-robot interaction forces (torques) or positional measurements of the robot is needed to determine the patient's intentions and abilities. The robot's assistance during therapy should be smooth to allow a pleasant interaction [14]. The recognition of the patient's movement intentions and motor abilities is a great challenge in patient-cooperative control systems. Bimanual training can use the unaffected limb to indicate the patient's movement intentions, while motor abilities can be assessed from forces applied by both hands.

Virtual reality environments are often combined with robotic devices in rehabilitation to increase motivation and training effectiveness. Highly motivating environments that increase task engagement are important for motor relearning and recovery after stroke [15].

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 each individual patient. A robotic system designed in this way combines the positive effects of both bimanual training and patient cooperative adaptive robot assistance. The use of only one robot would make the training easier, and the design and development of the system would be less complex and more cost-efficient compared to a multi-robot system.

The paper presents the development and validation of a bimanual training system as a rehabilitation aid for hemiparetic patients. If a patient cannot perform the task with both arms in a coordinated way, the adaptive nature of the system increases the needed support of the unaffected arm, thus reducing the contribution of the paretic arm in the combined movement. A tracking game was developed to guide the training and increase motivation.

2. Methods

2.1. Hardware

The proposed bimanual training system is based on the haptic robot HapticMaster (FCS Control Systems) [16]. The HapticMaster robot system has been proven to be appropriate for research of upper-limb motor rehabilitation [17, 18]. It is an admittance-controlled robotic manipulator with a control loop rate of 2500 Hz. The existing 3 active d.o.f. of the robot were expanded with an extra active joint at the end of the HapticMaster kinematic chain to allow the simulation of an active steering wheel. Bimanual handlebars (Fig. 1) mounted on the robot end-effector independently measure forces generated by each arm using two 6-d.o.f. force and torque sensors (Fig. 2). The handlebars turn like a steering wheel and can actively resist the subject's steering.

A passive gravity compensation mechanism, suggested by Ono and Morita [19], was implemented to compensate the weight of the subject's upper extremities (Fig. 1).

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 provides programmable resistance to the movements (virtual inertia and virtual viscous damping) and can ensure the desired contribution

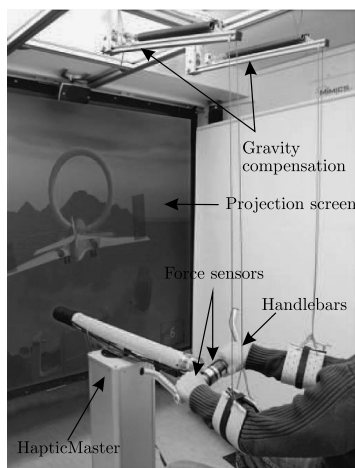


Figure 1. Subject during exercise.

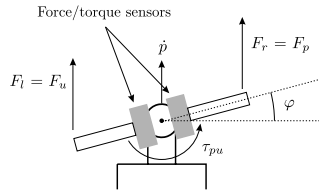


Figure 2. Bimanual handlebars mounted on the robot end-effector with two independent force/torque sensors (situation during vertical movements). The tangential forces along the direction of the desired movement are presented here for right hemiparetic subjects (F_l , left arm force; F_r , right arm force; F_u , unaffected arm force; F_p , paretic arm force). In addition, the orientation of the handlebars φ , velocity of the robot end-effector along the desired direction \dot{j} and torque applied by the subject τ_{pu} are introduced.

of both arms. The reaction force of the robot depends on the predefined admittance model and the virtual fixtures constraining the movement trajectories.

2.2. Training Exercises

As presented by Johnson *et al.* [8], a steering task is appropriate for bimanual training of post-stroke subjects. The main goal of their study was to encourage the correct usage of forces of both arms to complete a simple steering task. We propose to augment this approach. Our goal is to stimulate coordinated use of both limbs during bimanual tracking exercise. To do so, we decided to allow the user to move in two independent directions as opposed to the 1-d.o.f. in the Driver's SEAT [8]. The augmented approach allows significantly larger range of movements, stimulation of activation of specific arm muscles and uses the steering function only to impose coordination between both arms.

Training exercises were designed to be performed in the sagittal plane in front of the subject, predominantly in the vertical or horizontal direction depending on the exercise type. 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. 3. The user must coordinate both arms to keep the tracker object orientation constant, to prevent the tracker object from rotating.

If the paretic arm is not able to perform as required, the forces applied by the unaffected limb are scaled down using an adaptive gain to stimulate use of the paretic limb. The scale factor depends on the average orientation error e_φ between the reference and the tracker object. The sign of e_φ depends on the paretic arm. The positive e_φ is defined as the rotation that occurs when the unaffected arm applies greater forces to the handlebars than the paretic arm. For subjects with their right arm affected, the positive error is oriented clockwise; for subjects with their left arm affected, it is anticlockwise. Scaling down the unaffected limb forces means that higher combined effort of both arms is needed to complete the task. Namely,

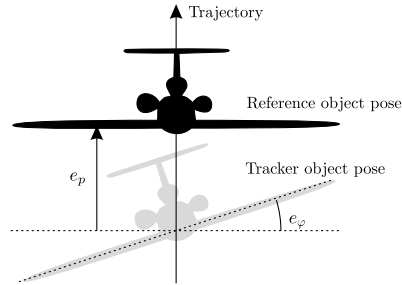


Figure 3. Movement trajectory, reference pose, measured pose of the robot end-effector (handlebars) and tracking errors e_p , and e_φ .

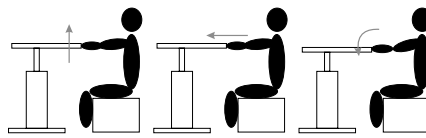


Figure 4. Different exercises (active movement is indicated by the arrow).

the force of the unaffected arm is scaled down before it is used in the admittance-controller of the HapticMaster robot. 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. e_p is defined as the difference between the reference position and the actual position of the handlebars. If the subject lags behind the reference, the error is positive; when the tracking objects moves ahead of the reference, it is negative. Nonetheless, the force ratio between the arms remains the same.

Three different tasks (Fig. 4) were designed to stimulate training of different muscle groups. The tasks are intentionally kept simple to isolate the activation of specific muscle groups. The robot is programmed to constrain the motion of the handlebars to the trajectory of the selected exercises (tasks):

- (i) *Vertical movement*: flexion of the shoulder joint with extended elbow joint.
- (ii) *Horizontal movement*: extension of the elbow joint and protraction of the shoulder joint.
- (iii) *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 the arrow direction in Fig. 4 and return movement in the opposite direction. For each task, the range of movement was approximately 20 cm. The stimulated movements are described above and stimulate the patient to use the less active (weak) muscle groups against resistance produced by the robot. The resistance stimulates

sensory-motor system activation in the stimulated direction and is not used in the opposite (return) movement since stroke patients usually over-activate these muscle groups [20].

Two unimanual exercise modes were implemented as a validation method. The two unimanual modes require performing the tasks using 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 to allow the tasks to be performed using only one arm. A comparison of unimanual training with the unaffected and paretic arms was performed to assess effects of the bimanual training. Unlike the bimanual mode, the unimanual mode focuses on positional tracking and not on the tracker object orientation. The unimanual modes enable objective measurement of motor performance improvement, while the bimanual mode was primarily intended as a training exercise.

2.3. Control Strategies

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

2.3.1. Adaptive Assistance Control

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, the unaffected arm can assist with a larger contribution to the combined movement. The main control goal is for the paretic arm to contribute as much as possible toward tracking the reference object.

The forces applied by the impaired arm are used in the robot controller as measured, but the forces applied by the unaffected arm on the handlebars are scaled down with the adaptive gain K_φ . The virtual adaptive forces used for robot control are defined as:

$$F_u^* = K_\varphi F_u \quad (1)$$

$$F_p^* = F_p, \quad (2)$$

where F_u and F_p are the measured tangential forces of the unaffected and paretic arm along the direction of the desired movement (the tangential component is used as a scalar value), respectively, F_u^* and F_p^* are the corresponding virtual adaptive tangential 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 the learning law [13]:

$$K_{\varphi,i+1} = (1 + \mu_\varphi)K_{\varphi,i} - g_\varphi e_\varphi, \quad (3)$$

where $0.2 \leq K_\varphi \leq 1$. $K_{\varphi,i+1}$ is the adaptive gain at discrete time step $i + 1$ and e_φ is the orientation error of the tracker object. The positive e_φ is defined as the rotation that occurs when the unaffected arm applies greater forces to the handlebars than the paretic arm. For subjects with their right arm affected the positive error is oriented

clockwise; for subjects with their left arm affected, it is anticlockwise. μ_φ is the forgetting factor and g_φ is the learning gain. Variables μ_φ and g_φ are experimentally defined gains. Positive learning ($e_\varphi < 0$) is allowed, but K_φ is limited to $0.2 \leq K_\varphi \leq 1$.

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:

$$F_c = F_p^* + F_u^* = F_p + K_\varphi F_u. \quad (4)$$

However, since the force of the unaffected arm is scaled down by the factor K_φ , the overall control force is reduced, thus increasing the effort required to move an admittance-type robot. This is generally desirable since the aim is to stimulate the use of the affected limb. However, if the required effort 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 effect:

$$K_{p,i+1} = (1 - \mu_p) K_{p,i} + g_p e_p, \quad (5)$$

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

$$F_c^* = K_p (F_p^* + F_u^*) = K_p (F_p + K_\varphi F_u). \quad (6)$$

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 $K_p = 1$.

2.3.2. Robot Admittance Control

The adaptive control force F_c^* defined in (6) is used in the HapticMaster admittance-controller to compute the position and velocity of the robot end-effector using a simple second-order dynamic model:

$$F_c^* = m \ddot{p}_r + b \dot{p}_r, \quad (7)$$

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

The reference position p_r and velocity \dot{p}_r are computed from (7), and then used in the robot PD position controller not presented here.

2.3.3. Model of the Steering Wheel

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

$$\tau_{pu} = I \ddot{\varphi}_r + B \dot{\varphi}_r + K \varphi_r \quad (8)$$

$$\tau_{pu} = r (F_r^* - F_l^*). \quad (9)$$

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 (8) φ_r and $\dot{\varphi}_r$ are computed and used as reference orientations for the robot PD orientation controller.

2.4. Virtual Environment

A virtual flight simulator environment (Fig. 5) was developed using Unity3D software for game design (Unity Technologies) to enhance subject's motivation. Two jet planes are displayed on the screen in front of the subject. A 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.

The visualization is somewhat altered (Fig. 5b), for better representation of forces involved in the horizontal movement. During the horizontal movement, the handlebar rotation does not depend on the horizontal forces being applied to it. Thus, the rotation of the handlebars is locked and the roll rotation of the plane is replaced by the rotation around the vertical axis (yaw rotation). The yaw angle is defined using dual equations to (8) and (9).

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

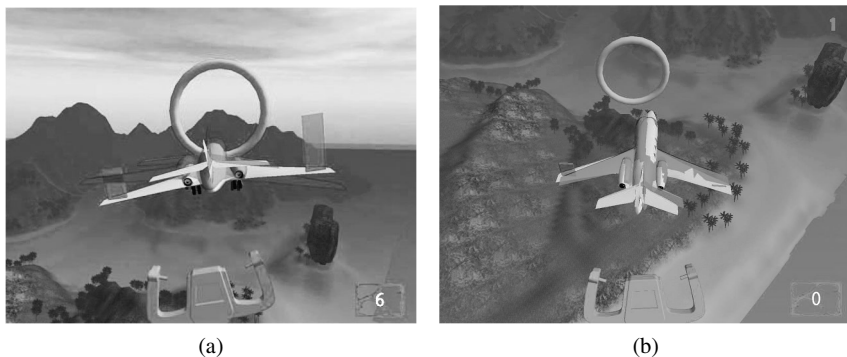


Figure 5. Virtual flight simulator environment. (a) Vertical movement and elbow extension. (b) Horizontal movement.

As additional help, two bars on both wings of the tracker plane are displayed. Their height represents the forces of each arm in the direction of the desired movement. The desired flight direction is represented by targets (orange circles).

2.5. Experimental Protocol

Four chronic hemiparetic subjects (S1–S4) participated in a pilot study. Their basic characteristics are summarized in Table 1.

Clinical scores are provided so that subjects' motor functions can be evaluated and so that the subjects can be compared between each other. To specify the level of impairment, muscle tone and upper extremity functions were assessed using the Modified Modified Ashworth Scale (MMAS) [21] and Motor Assessment Scale (MAS) for stroke [22], respectively. No severe limitation of passive range of motion in the upper arm joints was observed. The subjects have slightly (grade 1) to markedly (grade 2) increased muscle tone in majority of the commonly affected muscle groups after stroke; these are shoulder adductors and internal rotators, elbow flexors, and wrist and finger flexors. Additionally, muscle tone was increased in some other muscle groups. In S2, muscle clonus was present during assessment of muscle tone (Table 2). All subjects were able to perform the activities of the 'up-

Table 1.

Characteristics of four chronic hemiparetic subjects (S1–S4)

Patient data	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

Table 2.

Muscle tone by MMAS (0 = no increase; 1 = slight increase; 2 = marked increase; 3 = considerable increase; 4 = rigid part; subjects S1–S4)

Muscle group	S1	S2	S3	S4
Shoulder adductors	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 ^a	0	0
Fingers II–V flexors	0	2 ^b	3	1
Thumb flexor	2	0	0	0

^a Clonus debilitates after few contractions.

^b Clonus debilitates after multiple contractions.

Table 3.

Upper-arm function by MAS (0 = performance not possible; 6 = normal subject performance; subjects S1–S4)

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

per arm function' item of MAS, although their grades differed significantly (from minimal (grade 1) to normal subject's performance (grade 6)). Two subjects were able to perform the tasks of the 'hand movements' item, while only one subject performed the task of the 'advanced hand activities' item of MAS. Impairment of the upper-arm function was the most severe in S2, followed by S1, S3 and S4 (Table 3).

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 4 weeks (a total of eight sessions). Each training session consisted of the three exercises described earlier. The exercises were performed in this specific order: Vertical movement → Horizontal movement → Elbow extension. Each exercise was first performed 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. The total time of one session was approximately 30 min.

2.6. Electromyography

An electromyogram (EMG) was recorded in one session for one subject (S1) to assess the muscle activation during bimanual training. We want to use the EMG measurements to examine if the applied forces are a good representation of the actual muscle activation. With the use of the EMG, we can compare the activation of certain muscle groups of the paretic limb during unimanual and bimanual task execution. The EMG was recorded on four arm muscles (trapezius, deltoid, biceps brachii and triceps brachii) on the paretic and on the unaffected arm. EMG signals were collected at a sampling rate of 4800 Hz [23]. The EMG was filtered using a band-pass filter with cut-off frequencies of 20 and 500 Hz as well as a 50-Hz notch filter. For visualization, the moving average of the signal and the mean value 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.

3. Results

Force and positional data and all controller variables were collected at a sampling rate of 100 Hz while the subjects performed exercises. In offline analysis only stimulated movements were considered and data collected during the return movements were discarded.

One of the adopted evaluation criteria was the relative power produced by the unaffected and paretic arms. The power was computed from the forces applied by the subject to the handlebars and the robot movement velocity:

$$P_l = (\dot{p} - r\dot{\varphi})F_l, \quad P_r = (\dot{p} + r\dot{\varphi})F_r, \quad (10)$$

where P_l is the power applied by the left arm and P_r is the power applied by the right arm. Variable \dot{p} is the translational velocity of the robot, while $\dot{\varphi}$ is the rotational velocity of the handlebars.

The relative power of the paretic arm is then:

$$P_{\text{rel}} = \frac{P_p}{P_p + P_u} \cdot 100\%. \quad (11)$$

For left hemiparetic subjects, power of the paretic arm is $P_p = P_l$ and the power of the unaffected arm is $P_u = P_r$. For right hemiparetic subjects, $P_p = P_r$ and $P_u = P_l$. Healthy subjects could easily perform the tasks with the $P_{\text{rel}} \approx 50\%$.

The median of the relative power of all subjects in all sessions and types of bimanual exercises is shown in Fig. 6a. The data are displayed for each subject separately. For two of the subjects, relative power was near 50% through all sessions. In the first sessions, the other two subjects obtained worse results when using the paretic arm. After a couple of sessions, the power ratio of both arms significantly improved. This can be best observed for task 1 and partially also for task 2, while all subjects have the power ratio near 50% for task 3.

Tracking performance was evaluated based on orientation and position tracking errors. One important parameter is the median rotation of the virtual plane while performing the exercises. Positive rotation error is defined as turning to the left for left hemiparetic subjects and right for right hemiparetic subjects. In both cases, a positive rotation error is a consequence of larger forces of the unaffected arm. The median rotations of the tracker plane for all three exercises are presented for each subject in Fig. 6b. As can be expected, the majority of the rotational errors are positive, since the unaffected arm forces are greater than the forces of the paretic arm. A similar decrease of error values, mainly in task 1, is observed through sessions, as with relative power in Fig. 6a.

Figure 7 shows the root-mean-square (RMS) values of positional tracking errors for different tasks in bimanual mode. In the first sessions, the tracking errors for all four subjects were relatively large. After a few (two to five) sessions, the tracking error decreased to a smaller and more constant value.

The adaptive gain K_φ changes according to the force ratio of both arms in bimanual tasks. Figure 8 shows the dependence of the adaptive gain on the P_{rel} . The

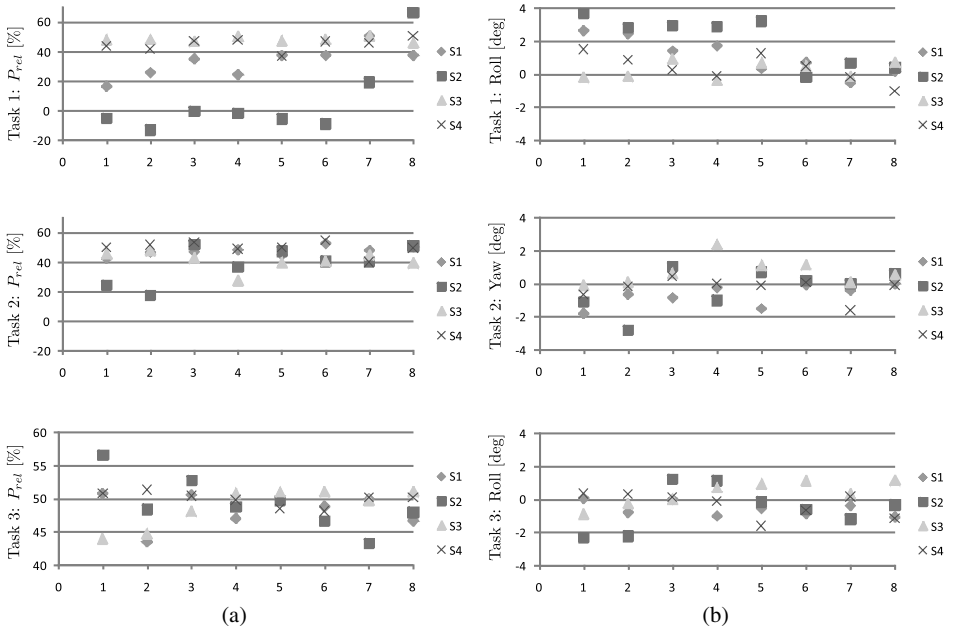


Figure 6. (a) Relative power of the paretic arm defines how much of the total power is produced by the paretic arm (note different scale for task 3). (b) Median orientation error. For vertical movement (task 1) and elbow extension (task 3) the roll orientation error is presented, for horizontal movement (task 2) the yaw error is shown. The x-axis shows the number of the session; subjects S1–S4.

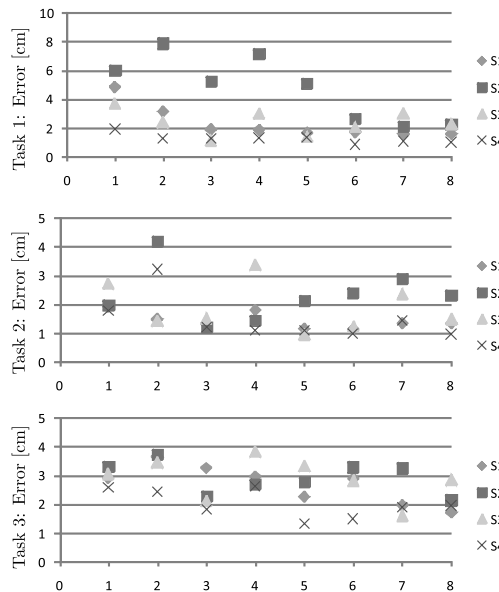


Figure 7. RMS tracking errors for each subject (S1–S4), task and session, shown on the x-axis.

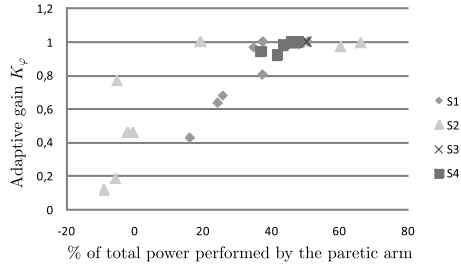


Figure 8. Adaptive gains K_φ for each subject (S1–S4) and session in relation to the relative power of the paretic arm.

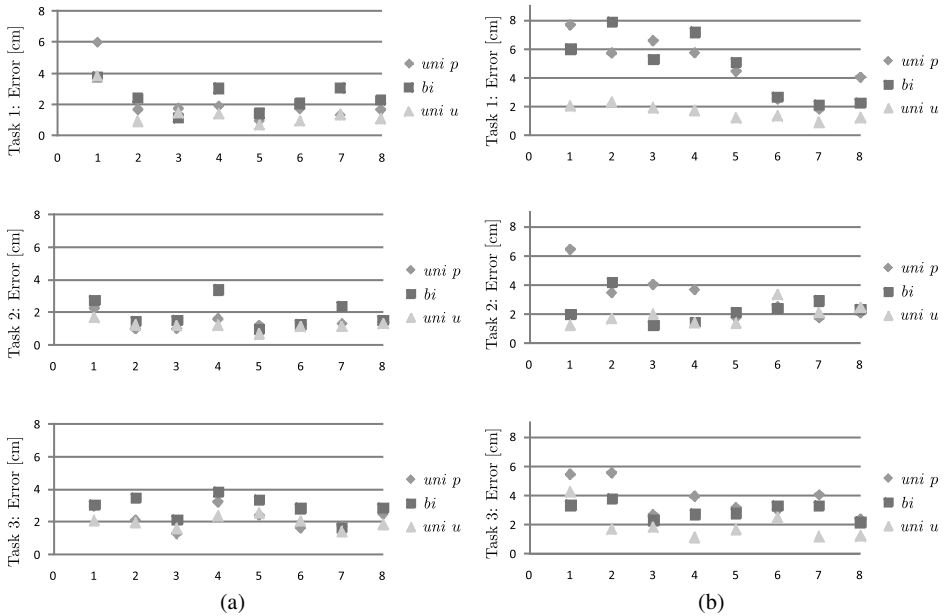


Figure 9. RMS tracking errors for subject S3 (a) and S2 (b) by sessions: unimanual paretic arm movements (*uni p*), bimanual movements (*bi*) and unimanual unaffected arm movements (*uni u*). The x -axis shows the number of the session.

chart shows the data for the first task. The subjects performed well in the third task, resulting in $P_{rel} \approx 50\%$ and $K_\varphi \approx 1$.

For validation of the system, the comparison of unimanual and bimanual exercises is shown in Fig. 9. 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 a less affected subject is S3, whose tracking errors are shown on Fig. 9a. Subjects S1 and S4 have similar results to those of S3. The tracking errors for all three modes follow a similar pattern. In the first session, the tracking error in task 1 was relatively large. In the following sessions, the errors were relatively small and constant. Tasks 2 and 3 show smaller and more constant values through all sessions.

No major differences were observed for three exercise modes, indicating that subjects were able to also use their paretic arm. This is in agreement with their motor scores. Figure 9b presents the results for subject S2, which are distinguishably different from the other three subjects. A greater difference between the paretic and the unaffected arm in unimanual mode can immediately be 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 deltoid muscle of the paretic and unaffected arm of subject S1 during the unimanual and bimanual vertical movement are shown in Fig. 10a. The activations of the paretic deltoid muscles during

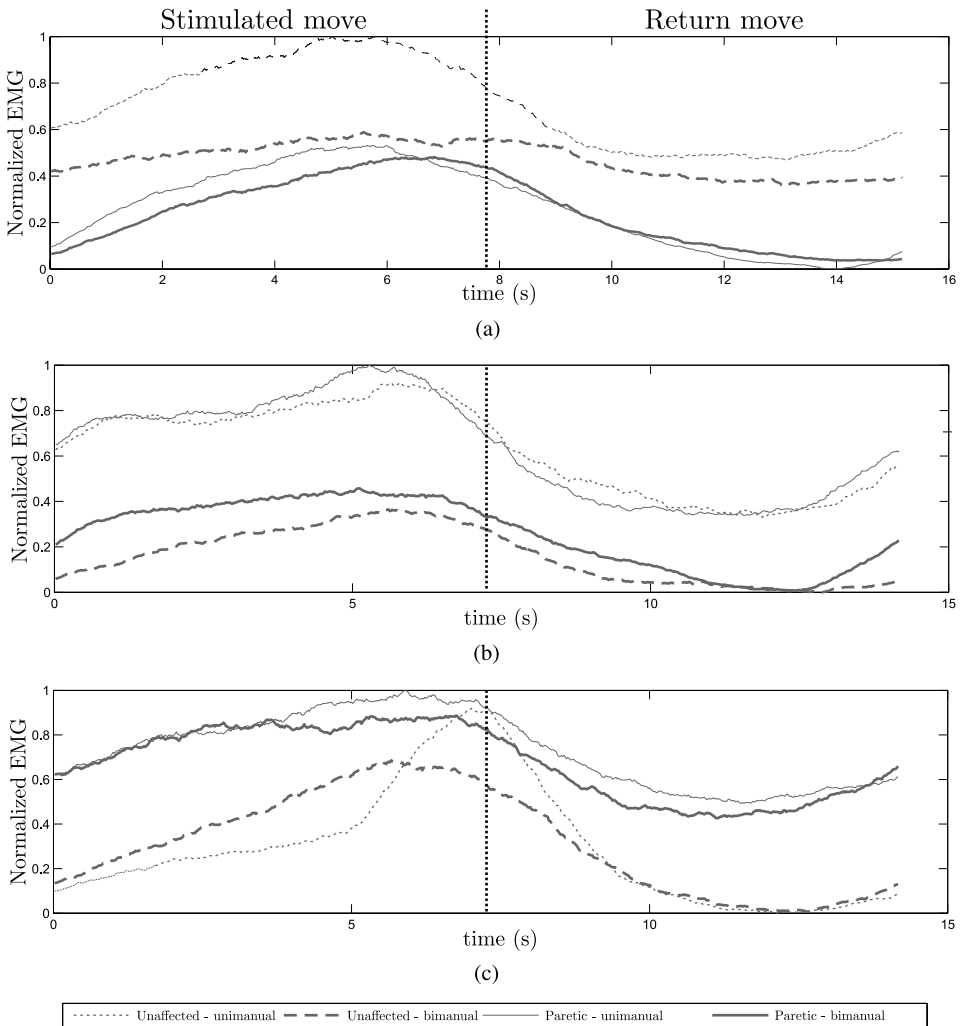


Figure 10. Normalized EMG of the deltoid muscle during vertical movement (a). EMG of the deltoid muscle (b) and trapezius muscle (c) during horizontal movement.

the unimanual and bimanual movement are very similar. During bimanual movement the activation of the unaffected deltoid is greater than the activation of the paretic muscle. The median relative power (11) of the paretic arm for the vertical movement in this particular session was $P_{rel} = 29.6\%$. The activation ratio of the deltoid muscle of both arms is similar to the power ratio applied to the handlebar.

During the horizontal movement, the activation of deltoid and trapezius muscles is stimulated. The filtered, scaled and averaged EMG signals of both deltoid muscles are presented in Fig. 10b. The activations of the paretic and unaffected arm deltoid muscle during the bimanual exercises are relatively similar, but both lower compared to the unimanual mode. The EMG signals of the trapezius muscles (Fig. 10c) 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. It can be seen in Fig. 10 that the paretic arm was more activated than the unaffected arm. This is confirmed by the relative power of the paretic arm $P_{rel} = 58.9\%$.

During the elbow extension task, the biceps and triceps muscles follow a similar pattern.

4. Discussion

The paper presents the development and validation of a novel system for bimanual training in rehabilitation of stroke patients. The pilot study with four hemiparetic subjects shows promising results. After eight training sessions and with the teaching of correct movements by a physiotherapist during bimanual training, the subjects were able to apply forces with the paretic arm similar to the forces of the unaffected arm.

Figure 8 shows the dependence of the adaptive gain on the percentage of the total power performed by the paretic arm during bimanual training. A lower power ratio of the paretic arm corresponds to a smaller adaptive gain K_ϕ . If the paretic arm is able to perform comparably to the unaffected one, K_ϕ remains close to 1. The adaptive nature of the system was found very appropriate for subjects with severe impairment. When the affected arm was too weak, the relative contribution of the unaffected arm was adapted accordingly. For subjects who could perform the desired task with good inter-limb coordination, the adaptive gain did not change significantly. The gain K_p required adaptation only for subject S2. With the other subjects, the RMS tracking error remained below 3 cm, under which the gain K_p did not change significantly.

Two of the subjects (S3 and S4) performed bimanual exercises well in all eight sessions. Their relative power of the paretic arm remained close to 50% (Fig. 6a). Subjects S1 and S2, on the other hand, improved throughout the training. In the first sessions S2's paretic arm even opposed the unaffected arm. However, the coordination between arms improved over time and errors decreased. Similar improvements

were observed for S1. By the last session, all subjects were able to perform the task correctly.

As subjects improved the power ratio of both arms, a decrease of median orientation errors can be observed for all three tasks (Fig. 6b) and is most noticeable for task 1. In accordance with previous findings, the positional RMS tracking errors for bimanual training (Fig. 7) also show a decreasing trend with sessions possibly indicating the improvement of the paretic arm motor performance. This is most apparent for tasks 1 and 3.

Subjects needed one or two sessions to get used to the system and the exercise type. After a learning period, the performance stabilized at a certain level. For less impaired subjects S1, S3 and S4 (e.g., subject S3 presented in Fig. 9), no significant differences can be observed between bimanual and unimanual training (using paretic or unaffected arm). Once accustomed to the system, the subject could perform tasks with the paretic arm almost as well as with the unaffected arm. Motor abilities of the paretic arm allow these subjects to perform the exercises similarly in bimanual and unimanual modes.

On the other hand, the most impaired subject (subject S2 in Fig. 9b) shows greater differences among the three exercise modes. Unimanual training with the paretic arm results in greater tracking errors than with the unaffected arm. The bimanual training shows similar errors as unimanual training with the affected arm. This indicates that the affected limb limits the combined performance of both arms together.

Unimanual exercises have the rotation of handlebars and plane disabled so the subject can focus on his/her position tracking performance. The bimanual exercises are more complex than unimanual modes. The subjects have to concentrate on two tasks — positional tracking and maintaining the correct orientation of the plane. As several degrees of freedom have to be controlled, bimanual exercises require the control (coordination) of a greater number of muscle groups and, therefore, proved to be harder to perform.

Although the EMG was recorded for only one session, it confirms the data given by the force sensors. The activation of the muscles of the paretic limb during the bimanual exercise is at least as high as the activation during the unimanual exercise of the paretic limb.

Research on 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 [24]. In our study, the Pearson correlation between tracking performance (RMS tracking errors) for bimanual training and tracking performance for unimanual training with 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 of the paretic limb. When biman-

ual performance improved, the unimanual performance using the paretic limb also improved significantly.

The approach to bimanual rehabilitation used in this study differs from the approaches used in other robotic systems in many ways. 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 the exercises. This approach is very intuitive and does not require long teaching times. Furthermore, the use of only one robotic device is more cost-efficient and the software design is less complex.

One possibility for the future implementation of our bimanual system is ‘mirror therapy’ [25]. Normally, the mirror provides patients with ‘proper’ visual input (i.e., the mirror reflection of the moving good arm looks like the affected arm moving correctly) and substitutes for the often decreased or absent proprioceptive input. The function of the mirror would be substituted with the bimanual robot system. The paretic arm would move along the same trajectory as the unaffected arm, enabling a ‘proper’ visual proprioceptive input.

5. Conclusions

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 task performance estimated from data provided by the robotic system. Subjects with greater impairment may benefit most from the adaptive support provided by the system.

The performed training improved the tracking performance of subjects participating in this study. The correlation between bimanual training and unimanual paretic arm performance is 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. Furthermore, the bimanual training addresses directly the problems related to patient-cooperative control of robotic systems. With bimanual training, benefits for unimanual use of the paretic arm are also observed.

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 applied principles stimulate the motor activity of the paretic arm, to move in a coordinated way with the unaffected arm.

In addition to training, the system could be 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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