Robot therapy for stroke survivors: proprioceptive training and regulation of assistance

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Abstract. Robot therapy seems promising with stroke survivors, but it is unclear which exercises are most effective, and whether other pathologies may benefit from this technique. In general, exercises should exploit the adaptive nature of the nervous system, even in chronic patients. Ideally, exercise should involve multiple sensory modalities and, to promote active subject participation, the level of assistance should be kept to a minimum. Moreover, exercises should be tailored to the different degrees of impairment, and should adapt to changing performance.

To this end, we designed three tasks: (i) a hitting task, aimed at improving the ability to perform extension movements; (ii) a tracking task, aimed at improving visuo-motor control; and (iii) a bimanual task, aimed at fostering inter-limb coordination. All exercises are conducted on a planar manipulandum with two degrees of freedom, and involve alternating blocks of exercises performed with and without vision. The degree of assistance is kept to a minimum, and adjusted to the changing subject’s performance. All three exercises were tested on chronic stroke survivors with different levels of impairment. During the course of each exercise, movements became faster, smoother, more precise, and required decreasing levels of assistive force. These results point to the potential benefit of that assist-as-needed training with a proprioceptive component in a variety of clinical conditions.

Keywords. Robot therapy, stroke, rehabilitation

Introduction

During the last few years, considerable effort has been devoted to using robots for delivering therapy to persons with motor disabilities [1, 2]. Robotic devices have been frequently used to enforce passive movements (see Figure 1, left). In fact, it has been shown that repeated passive exercise may help improving recovery[3, 7]. However, a number of studies [8, 10] point at techniques that take the adaptive nature of the nervous system into consideration. Such techniques include active-assisted exercises, in which the robot guides the arm along a desired path (see Figure 1, right). A variant is

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represented by active-constrained techniques, in which the robot only allows movement when the limb forces are appropriately directed toward the target. In contrast, in active-resisted exercises the robot provides resistance to the desired movement. Furthermore, in adaptive exercises the robot provides an unfamiliar dynamic environment, which requires the subject to adapt. Active-resisted and adaptive techniques imply the presence of a sufficient residual voluntary function, but are not viable options for severely impaired subjects, who may lack autonomous control of their movements. On the other hand, these subjects may benefit from therapeutic protocols in which a sufficient level of assistance allows them to exploit their residual abilities.

In this chapter, we review a number of studies on using robots with chronic stroke survivors. In particular, we suggest that rehabilitation protocols should involve vision and no-vision (proprioceptive) training, and that assistance should be kept to a minimum.

**Motor learning and the role of assistance**

Most robot therapy protocols tested in clinical trials use a combination of active and passive training [1, 2]; therefore, it is hard to draw solid conclusions on their relative merits. Some indications on what exercises are more effective may come from a better understanding of the neural basis of motor learning.

The mechanisms of action of physical assistance in promoting motor learning or re-learning are poorly understood. Assistive forces help subjects complete the motor task, which in turn may increase subject motivation, even in the early phase of the learning/recovery process. Furthermore, assistive forces may elicit the right afferent signals (proprioceptive, tactile), thus promoting the emergence of the appropriate associations in sensory and motor cortical areas. In addition, assistive forces may affect learning by inducing a sensation of greater stability of the external environment, or some aspects of it a necessary condition for long-term, more stable adaptation to occur [11].

In the simplest form of assisted exercise, the robot has complete control of the task. This may be beneficial, but as learning (or re-learning) progresses, the differences between physically guided and active movements become more important. Passive (completely assisted) movements provide feedback that is different from that of active movements. In fact, in motor learning studies, the benefits of physical guidance for motor learning have mainly been ascribed to its early phase, when the motor pattern is brought into the ‘right ballpark’, e.g. [12].

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**Figure 1.** Passive (left) and Active (right) training modalities
The learning process may be facilitated if augmented feedback is provided on selected aspects of performance and/or the outcome of the movement[13]. In fact, assistance may be seen as a form of augmented feedback that emphasizes performance on specific aspects of the task.

Overall, these considerations suggest that in order to be effective, assistance should be highly task-specific. Recent studies indicate that only the task-relevant features of a movement are explicitly controlled by the nervous system [14]. The remaining degrees of freedom would be specified through an on-line optimisation process. This would suggest that assistance should be limited to specific (task-relevant) features of the movement.

According to this view, assistance would take the general form of a feedback controller, with proportional (position-dependent) and derivative (speed-dependent) components. An alternative view [15] is that assistance continuously generates the forces that the impaired arm cannot provide by itself, so that the movement is as normal as possible. In this view, assistance would take the form of a controller which involves an explicit model of the (impaired) arm and its neural control.

The ultimate goal of robot therapy is to emulate as closely as possible a (good) human physical therapist. This would suggest, at least in perspective, to look at the patterns of patient-therapist interaction from the point of view of the modalities of assistance outlined above. This would also allow to identify which combination of feedback and feed-forward control is actually embodied by human therapists.

Robot-assisted exercise may be seen as a form of cooperative control, in which the robot and the human subject aim at achieving a common goal. The aim is to gradually transfer control from the robot to the human.

**Regulation of assistance**

Recently, a few studies have addressed the way assistive forces affect motor performance and/or motor learning [16]. When moving under the effect of assistive forces, provided by a robot agent, humans tend to quickly incorporate these forces in their motor plan. More specifically, the motor system appears to behave as a ‘greedy’ optimiser, which exploits the assistive forces in order to reduce the amount of voluntary control (and therefore muscle activation), while keeping the position error small. This strategy would minimize effort while maintaining the required performance. As a consequence, during active-assisted exercises (and, even more, during passive training), a constant-magnitude assistive force would gradually depress voluntary control; it has been suggested that this would have adverse effects on recovery. To prevent this, assistance should be reduced to a minimum (assist-as-needed), and continuously regulated as a function of the observed outcome[17].

Ideally, assistance should be adjusted with respect to the current amount of voluntary control. As the latter is not readily available, most schemes of regulation are driven by the observed performance; see Figure 2.
Are there ‘optimal’ ways to provide assistance, and to continuously regulate it? If this is the case, do they depend on the specific task, or do they obey to general principles, valid for a wide range of motor learning problems? While optimal solutions have been proposed for simple, specific tasks, like lifting a weight [18, 19], it would be desirable to derive general principles and methods, that can (in principle) be applied to any motor learning/re-learning task.

Recently, Wolbrecht and coll. [15] proposed an adaptive control scheme, in which a controller negotiates an error-reducing and an effort-reducing component. This allows to keep assistance to a minimum and to automatically adapt it to task performance, while providing enough assistance to support task completion. This technique does not explicitly aim at augmenting the degree of voluntary control. Such an increase is assumed to result from the ability to successfully complete the task.

**Proprioceptive training**

In stroke survivors, motor impairment is frequently associated with degraded proprioceptive and/or somatosensory functions [20]. Stroke subjects may have difficulties with estimating the position of their arm in absence of vision. Moreover, they may be unable to integrate visual and proprioceptive information. Furthermore, when performing assistive training they may not be capable of detecting the presence, magnitude and direction of assistive forces. Therefore, impaired proprioception may affect the recovery of motor functions [21]. Like motor deficits, proprioceptive deficits may decrease through repeated exercise [22]. The nervous system uses flexible strategies in integrating visual and proprioceptive information [23]: when both visual and kinesthetic information of a limb are available, vision is usually the dominant source of information [24, 27]. As a consequence of visual dominance[28, 30], proprioceptive impairment may be masked by vision if the latter is available. This would suggest that in subjects with both proprioceptive and motor impairment, assistive exercise might be more effective if at least part of the training were performed without vision. In fact, recent studies demonstrate that visual feedback is not necessary for learning novel dynamics [31].

In this context, the contribution of robotic devices to neuromotor rehabilitation may turn out to be crucial. Moreover, different training conditions - either presence or
absence of vision - may have different degrees of efficacy in robot therapy protocols in individual stroke patients.

1. Statistical models to assess recovery

A problem of protocols based on variable degrees of assistance for severely impaired subjects is that the amount of voluntary control (i.e., the performance in absence of assistance), as well as its change due to exercise, cannot be inferred from trials in which assistance is removed - in this case, patients would be unable to perform the task and is not immediately observable when looking at performance in assisted trials [32]. Moreover, if the training is tailored to individual subjects such that the level of assistance decreases with improved performance, treatment protocols will tend to differ widely across subjects, which makes comparisons difficult.

A similar problem occurs if therapy protocols include training with both eyes open and eyes closed. The effect may be highly variable from subject to subject, depending on the nature of their impairment. Subjects with impaired proprioception may perform better in the presence of vision. Subjects with problems in integration of proprioceptive and visual information may perform better in absence of vision. In these different situations, visual feedback is likely to have different effects. This highlights the need for analytic tools that can explore this form of between-subjects variability.

One possible way to address these problems is to use a statistical model which separately accounts for the effects of exercise, vision and degree of assistance on the overall performance, while taking into account individual variations. Such a model would allow for well defined statistical hypothesis testing (e.g. is the treatment effective?) and analysis of inter-subject variability.

This may be done with a mixed-effects model, with three fixed effect factors plus an interaction term (session, force, vision, session × vision interaction) and one random factor (subject), to properly account for the correlations among repeated measures from the same subject. The deterministic part of the model is defined as:

\[
\text{performance} = b_0 + b_1 \cdot \text{session} + b_2 \cdot \text{force} + b_3 \cdot \text{vision} + b_4 \cdot (\text{session} \times \text{vision})
\]  

where \(\text{session}\) is the session number (from 0 to max), \(\text{force}\) is the intensity of the assistive force (in N), and \(\text{vision}\) denotes absence (0) or presence (1) of vision.

Model coefficients may be interpreted as follows: (i) \(b_0\) is the ‘baseline performance level’, i.e. the performance at the initial session, with zero assistive force; this corresponds to the initial degree of voluntary control; (ii) \(b_1\) is the between-session rate of improvement; (iii) \(b_2\) is a ‘compliance’ coefficient, measuring the sensitivity of performance on the assistance level; (iv) \(b_3\) is the ‘vision’ component, which indicates the contribution to the performance provided by presence of vision; (v) \(b_4\) is the ‘session × vision’ component, which accounts for the differences in the session effect that are due to vision. In other words, \(b_4\) accounts for the different behaviors, in terms of between-session improvement, of vision and no-vision trials.

The presence of random factors implies that the above model parameters can be seen as having a constant component (the same for all subjects), and a random component (different for each subject), which can be estimated separately.

Testing the significance of the ‘fixed’ components allows to test hypotheses like whether the therapy produces a significant improvement (this would correspond to
testing for the significance of the ‘session’ effect). If we consider the whole set of parameters (i.e., fixed plus random), we can look at inter-subject variability. For instance, we may look at the relationship between the baseline performance \(b_0\) and the subsequent improvement \(b_1\) in no-vision sessions. Or, we may look at the difference in baseline performance between vision and no-vision trials \(b_3\) and the corresponding difference in improvement between the same trials \(b_4\).

For each particular task we need to define a suitable indicator of performance. Then, the model can be fitted to the data by using a maximum-likelihood procedure [33] – for instance, in the R statistical package, this is done by the ‘lme’ function library [34]. The fitting procedure provides estimates for the fixed and the random components of each model coefficient, as well as the corresponding significance scores.

2. Experiments

We carried out three pilot studies to investigate the potential benefit of active assisted training in the recovery of arm movements after stroke. The training included an explicit proprioceptive component. In all cases, subjects performed their movements under the influence of robot-generated assistive forces.

We focused on chronic stroke survivors, who were initially unable to complete the required movements with their affected arm without assistance. The inclusion criteria were chronic conditions (at least 1 year after stroke) and stable clinical conditions for at least one month before entering the study. The exclusion criteria were the inability to understand instructions about the exercise protocol, and the presence of other neurocognitive problems.

In all cases, we used an ‘assist-as-needed’ protocol, in which the therapist initially sets the magnitude of the assistive force provided by the robot. Assistance allows patients to initiate the movements, but in no way imposes the trajectory, the reaching time, or the speed profile. Whenever patient performance improves, in the subsequent blocks of trials force magnitude is reduced - either manually or automatically. Part of the trials are performed without vision of the arm, so that subjects are forced to rely on proprioception to estimate the position of their arm and the direction/position of the target by detecting presence and direction of the assistive force.

All studies use the same robot system, specifically designed for robot therapy and for the evaluation of motor control and motor adaptation. The robot - Braccio di Ferro (BdF) is a planar manipulandum with 2 degrees of freedom [35]. It has a large planar workspace (a 80×40 cm ellipse) and a rigid parallelogram structure with direct drive of two brushless motors that provides a low intrinsic mechanical impedance at the end-effector and a full backdriveability. Hand trajectory is measured with high resolution (0.1 mm) through optical encoders, and an impedance controller modulates (from fractions of 1 N up to 50 N) the force transmitted to the hand. Therefore, motion of the hand is not imposed but results from the interaction between the forces generated by the robot and the forces generated by patients’ muscles. In all experiments, subjects sat in a chair, with their chest and wrist restrained, and grasped the robot handle. A light, soft support was connected to the forearm to allow low-friction sliding on the horizontal surface of a table. In this way, only the shoulder and the elbow were allowed to move, and motion was restricted to the horizontal plane, with no influence of gravity.

The height of the seat was adjusted, so that the arm was kept approximately horizontal, and its position was also adjusted, in such a way that the farthest targets
could be reached with an almost extended arm. A 19” LCD screen was positioned in front of the patients at a distance of about 1 m in order to display the positions of hand and of the targets.

Due to the small size of the subjects population, these studies are merely intended as feasibility studies, aimed at demonstrating the proposed approach and the related analytical tools.

2.1. Hitting Task

This task [36] focuses specifically on facilitating the active execution of arm extension movements. This is motivated by the observation that many stroke subjects are unable to actively perform these movements, particularly in specific directions. In contrast, wide inward movements are dominated by the flexion pattern that characterizes this pathology. The task consists of hitting a set of targets, arranged in the horizontal plane (Figure 3, top) according to three layers: inner (A, 3 targets), middle (B, 3 targets), and outer (C, 7 targets). Reaching the outer targets requires nearly full extension of the arm. Target sequences were generated according to the following scheme: A→C→B→A. In this way, outward movements had to be performed in one step (A→C), whereas inward movements were performed in two steps (C→B and B→A).

When a target was presented to the subject, the robot generated an assistive force $F$, directed toward the target, $x_T$. The assistive force was delivered gradually with a ramp-and-hold profile, $R(t)$ that had a rise time of one second. The force was switched off as soon as the subject hit the target. The next target was presented after a pause of 1 s. Assistance also had a speed-dependent component, aimed at improving the interaction between the subject and the robot. A virtual wall also provided additional haptic feedback. The force generated by the robot is summarized by Eq. 2:

$$F(t) = F_A \frac{(x_T - x_H)}{[x_T - x_H]} \cdot R(t) - b \cdot v_H - k_W \cdot (x_H - x_W)$$

where $x_T$ is the vector that identifies the target position in the plane, $x_H$ and $v_H$ are, respectively, the hand position and speed vectors; $b$ (12 Ns/m) is the viscous coefficient, and $k_W$ (1000 N/m) is the stiffness coefficient of the wall. $x_W$ indicates the projection of hand position on the wall. The difference $(x_H - x_W)$ indicates the degree of ‘penetration’ of the hand inside the wall, and is zero outside the wall. The protocol started with a test phase, during which individual subjects became familiar with the apparatus and in which a physical therapist selected the minimum force level $F_A$ that evoked a functional response, i.e. a (possibly incomplete) movement in the intended direction.

One block of trials included repetitions of the A→C→B→A sequence with different targets in random order, for a total of 3×3×7=63 movements. Each block of trials was performed either with or without vision. In the latter case, the subjects were blindfolded, but could still feel the target through proprioception. The first training session initiated with two blocks of trials (vision, no-vision), using the same level of force determined in the test session ($F_1$). After a little rest, the therapist considered the level of performance and asked the subject about fatigue. The decision could be 1) to terminate the session, 2) to continue with the same force level, 2) to continue with a reduced force $F_2$ (10-20% less than $F_1$). The procedure was iterated until the decision to stop was agreed by the patient and the therapist. In following sessions the training always started $F_1$, and then, if possible, the level of assistance was decreased. If subjects reached a level of assistance with a force below 4 N, the no-vision blocks were
eliminated. The whole training protocol consisted of 10 sessions (1-2 sessions/week, about 1 hour each), plus the initial test session.

Nine stroke survivors (2 males, 7 females, age 52±14) participated in this study. Disease duration was 34±19 months (range 12-76), in which the majority were ischemic in nature (7/9). Patient impairment was evaluated by means of the Fugl-Meyer score, limited to the arm section (FMA) [37, 38]. The average FMA score was 15±13 (range 5-41). The average Ashworth score of muscle spasticity [39] was 1.9±0.9 (range 1-3).

2.1.1. Results

An example of a trial in an early and a late phase of training (Subject 5) is depicted in Figure 3, which shows (middle) the A→C→B→A trajectories and (bottom) the
corresponding time courses of assistive force and hand speed profile. Figure 3 shows
the trajectories in a typical subject. In early sessions, the outward movement (A→C) is
segmented into a sequence of sub-movements. The first sub-movement covers only
part of the total distance, thus leaving a residual error which has to be corrected by
additional movements. The motor performance in late training sessions (Figure 3,
bottom right) suggests a visible improvement. At the same time, the level of robot
assistance could be reduced from 12 N to 6 N; movement duration was shorter, and the
number of sub-movements was reduced. The residual error after the first sub-
movement decreases as well. In the overall population of subjects, the initial level of
assistance ranged between 25 N and 5 N, and was generally higher for patients who
initially had lower Fugl-Meyer scores (arm part).

To account for the joint effects of session and assistance, we applied the mixed-
effects model (see Eq. 1) to the number of sub-movement observed during the outward
phase of each trial. The number of sub-movements had a significant effect on the level
of assistance (p=0.0026). This is not surprising, the results merely confirm that
assistance has a beneficial effect on performance. The effect of session was also highly
significant (p<0.0001). In fact, we found a negative $b_1$ (session) coefficient (systematic
part): $-0.369\pm0.098$ sub-movements per session. This indicates that the observed effect
of session corresponds to a reduction of sub-movements. The model may also be used
to assess the session effect on each individual subject (Figure 4 - left). The number of
peaks displays a strong negative correlation (the correlation coefficient is -0.75)
between baseline performance, $b_0$, and the change over sessions, $b_1$: subjects with
better initial performance are closer to maximum performance and therefore they
improve less, however, irrespective of the initial conditions, all subjects have a
potential for improvement. With regard to the effect of vision, we found significant
vision and session × vision effects. This means the presence of vision did not have a
systematic effect. However, the model allows us to investigate the effect of vision on

![Figure 4. Effect of robot training on the number of sub-movements. Left: Baseline performance vs change over sessions. Improvement is greater in subjects with a greater initial impairment. Right: Different subjects exhibit different impairments with and without vision, but in all cases the effect of training is to equalize their vision-no vision performance. Dots indicate initial performance, lines the change over sessions.](image-url)
individual subjects. A crucial question is how the different subjects compare in terms of their initial performance with eyes open or eyes closed. Another question, similar to the one we asked before for the ‘session’ effect, is whether there is a systematic relationship between the differential behavior in vision and no-vision baseline behavior and the differential change in vision and no-vision trials. The former question can be addressed by comparing, for each subject, the baseline performance with vision \((b_0+b_1)\) and without \((b_0)\). Figure 4 (right) clearly indicates that some subjects (namely, S1 and S3) have a better initial performance with eyes closed (data points above the diagonal line). In contrast, other subjects (S8, S9) have better performance with eyes open (data points below the diagonal). The remaining subjects have similar performance with both sensory modalities.

The difference in the baseline performance with and without vision (i.e., parameter \(b_1\)) and the relative difference in the performance change over sessions (i.e., parameter \(b_4\)) have a strong negative correlation (correlation coefficient: -0.96). This means that subjects with severe impairments in the eyes closed condition (negative \(b_1\)) result in a greater improvement in eyes closed trials (negative \(b_4\)), and vice versa.

As regards FMA scores, we found a statistically significant change (\(p = 0.00035\), pairwise t-test) from \(15\pm13\) to \(20\pm13\), corresponding to an average \(4.8\pm2.4\) improvement. This is in line with previous studies [1], which report an average improvement of \(3.7\pm0.5\). Evaluation of the FMA at follow-up resulted in a substantial preservation of the improvement (FMA=20\pm13, no significant difference from that assessed at the end of treatment). Four subjects even displayed an improvement in their FMA score. No change was observed in the subjects’ Ashworth score.

### 2.2. Tracking Task

In this task [40], subjects had to continuously track a moving visual target, moving on a figure-of-eight trajectory (length = 90 cm, time period = 15 s). The target was represented visually as a small red circle, and haptically, as an attractive force field defined by \(F = K \cdot \sqrt{d}\), where \(d\) is the distance of the hand from the target (Figure 5). The current position of the hand was continuously displayed (as the picture of a small car). For each subject, the scale factor, \(K\), was initially selected as the minimum level capable to induce the initiation of movement; The range of the assistive force was 3-30 N (from the least to the greatest impairment). The moving target stopped if the distance from the cursor was greater than 2 cm. The experimental protocol was organized into blocks of 10 trials each, which include 10 repetitions of the figure-of-eight. Within each training session, two blocks of trials are alternated, with eyes open and eyes closed. Within each block, half of the trials were clockwise and half were counterclockwise. One session lasted approximately 45 minutes. At the end of each block, the robot estimated a performance score, based on the number of stops and the overall movement duration. If the score exceeded a threshold, the level of assistance was reduced. Unlike the previous exercise, assistance here is automatically adapted to the observed performance (see Figure 2).

The therapy cycle included up to 10 sessions (2-3 sessions/week). Improvements were evaluated with clinical scales (FMA, Ashworth) and movement indicators (average speed, duration, tracking error, stop time). We used the statistical model described in Section 1.
Ten chronic hemiparetic subjects participated in this study (3 M, 7 F, age=53±15y, disease duration=4±2y, Fugl-Meyer score - arm part (FMA): 23±14).

2.2.1. Results

Fig. 5 (bottom) displays changes in the tracking trajectories in a typical patient between the first and the last session. Statistical analysis resulted in highly significant effects of session for the mean speed (p<0.0001) At the mean speed, the effect of session was highly significant. The session effect resulted in an improved performance (increased speed). As regards assistance, we found no significant effects. This is no surprise, as the expected outcome of assistance regulation is that performance is relatively insensitive to assistance.

We found significant vision and session × vision effects. The presence of vision did not have a systematic effect likely due to the fact that subjects vary widely in their level of sensory impairment. However, the statistical model allows us to investigate the effect of vision on individual subjects. As in the previous experiment, two crucial questions are: (i) how the different subjects compare in terms of their initial performance with eyes open or closed, and (ii) whether there is a systematic relationship between the differential behavior in vision and no-vision baseline behavior and the differential change in vision and no-vision trials. Question (i) may be addressed by comparing the baseline performance with and without vision for each subject. We found that some subjects (S3, S6 and S8) have a better initial performance with eyes
closed, whereas other subjects (S1, S4, S5, S9) perform better with eyes open. The remaining subjects have similar performance with both sensory modalities.

We found a negative correlation ($r = -0.27$) between the initial vision/no vision performance difference and the difference in the vision/no vision improvement. This means that subjects with an initially more severe impairment with eyes closed resulted in a greater improvement in eyes closed trials, and vice versa. Improved performance is also reflected in the increased FMA score (from 23±14 to 27±15, corresponding to an average 3.4±1.9 increase). The level of assistance was reduced on average by 28%.

As in the previous experiment, subjects consistently improve their performance. Moreover, proprioceptive problems - revealed by a discrepancy between initial performance with eyes open and closed - tend to reduce over training.

2.3. Bi-manual training

Upper limb robot therapies for stroke hemiparesis primarily focus on the paretic limb, with unilateral exercises to improve motor control of the shoulder and elbow [1]. Actually, many daily tasks require the coordination of both hands. This points to a possible benefit of protocols for upper limb robotic rehabilitation that involve the cooperation of both hands. Few studies have examined the efficacy of bilateral training in the recovery of paretic limb movements post-stroke [3, 4, 41]. These studies showed a positive effect on joint power of the affected shoulder and elbow muscles, although motor control improved to a lesser extent. In these cases, however, the two arms were not required to cooperate but, rather, to interact in a master-slave fashion.

Here we propose a robot-mediated cooperative exercise, in which subjects make forward and backward movements with both hands, while grasping the handles of an horizontal bar. Subjects are required to keep the horizontal orientation of the bar. In this way, the plegic and non plegic limbs are required to coordinate and balance their action in order to achieve the movement goal. Bi-manual cooperation may be seen as a form of self-regulated assistance. The non-plegic limb contributes to the forward and backward translation of the bar, but the contributions of both arms must be balanced in

![Figure 6. The bi-manual task. Left: experimental apparatus. Right: assistive force fields.](image)
order to keep the bar horizontal.

For the purpose of this study, an horizontal bar (Figure 6, left) was connected to the end effector of the robot. Subjects grasped the two handles of the bar, symmetrically positioned with respect to the central hinge. The distance between the handles was adjusted to match the distance between the shoulders of the subject. Bar rotation was not actuated, but bar orientation was measured by a potentiometer.

Subjects sat in front of a computer screen, which displayed a target (a circle with a 2 cm diameter) and a green bar, indicating position and orientation of the bar; see Figure 6 (right). The task consisted of forward and backward movements (nominal path length: 20 cm), to be performed by maintaining the bar perpendicular to movement direction. If bar orientation exceeded a threshold angle (4°), the bar became red.

The robot generated four types of forces (Figure 6, right): 1) an assistive field, pulling the end effector toward the target. Its magnitude was set as the minimum value sufficient to promote active movement. This value was gradually decreased while subjects’ performance improved; 2) a strong resistive elastic field, only active when the orientation error was greater than 4°; 3) two vertical ‘walls’, that prevented horizontal movements; 4) a viscous field, which introduced a friction component for the stabilization of patients’ arms. The task was carried out in two conditions: with eyes open or eyes closed. In the latter case, subjects had no visual feedback, but the robot provided the necessary proprioceptive information: target direction and bar unbalance were denoted by the attractive and resistive fields, respectively. Each block of trials consisted of 10 repetitions of forward and backward movements, under one of the two conditions (open and closed eyes). Each session lasted about 30 minutes. The therapy cycle included up to 5 sessions (2-3 sessions/week). Movement trajectories were then analyzed.

Six patients with chronic stroke (3 M, 3 F) participated at this study. Subjects ranged in age from 32 to 74 years (58±16y), with an average post-stroke time of 3.5±1.4y. Their Fugl-Meyer score - arm part (FMA) was 14.3±8.6, and their Ashworth score was 2.2±1.4.

2.3.1. Results

Over sessions, the number of blocks of trials performed by the subjects increased, while the minimum level of assistive force decreased. Even though the difficulty of the exercise increased, subjects’ performance improved. Movement duration (Figure 7) and balance error (defined as the number of times bar orientation exceeded the threshold; Figure 7) decreased throughout the sessions. At the end of the training sessions, the task was carried out faster and with better coordination between the two limbs. Figure 7 suggests that backward movements are faster than forward movements, possibly because the flexion pattern that characterize this pathology has a more negative influence and is more difficult to control in backward movements. This is consistent with the findings in the Hitting task (see above). An improvement was found in both the vision and non vision conditions. In the closed eyes condition, performance tends to be worse in all subjects, except S5. In this situation subjects must rely solely on proprioception to estimate 1) the position of each arm in the workspace, 2) the position of one arm with respect to the other, and 3) the effect of one arm movement on the other arm.
These preliminary results suggest that bi-manual cooperative training may be beneficial to stroke survivors. Moreover, the results help to justify a full clinical trial with a control group and greater number of subjects, as well as more rehabilitation sessions.

3. Discussion

We have presented three examples of active-assisted training protocols, aimed at the rehabilitation of chronic stroke survivors. These exercises have a number of common features: (i) problem-solving aspects and a sensory-rich experience; (ii) a mechanism that regulates the degree of assistance such that it is kept to a minimum; (iii) different blocks of trials are performed with and without vision, in alternation.

In all three experiments, analysis of performance suggests that, all patients

![Figure 7. Performance of a typical stroke subject in the bi-manual task, at the beginning (left) and end (right) of the training protocol. Top: time course of vertical movements. Middle: bar orientation. Bottom: Attractive (assistive) and resistive forces.](image)
exhibited an increase in the amount of voluntary control, even though some of them could not achieve complete recovery of autonomous movements. In particular, we found that proprioceptive training (i.e., training with closed eyes) is beneficial to patients with abnormal proprioception. Moreover, training different sensory modalities separately may improve overall recovery.

These results highlight a number of key points, which will need to be accounted for when trying to improve the efficacy of robots as therapeutic devices. First, robot therapy should rely on a better understanding of the mechanisms underlying motor learning and re-learning. In particular, it is crucial to identify ‘optimal’ ways to provide assistance and to regulate it. Second, robots may be beneficial to neuromotor rehabilitation not only for their potential for improving motor control, but also because they may help to train multi-sensory and sensorimotor integration. Robots are capable of delivering interactive and repeatable sensorimotor exercises and continuously monitoring the actual motor performance. They can also be used to simulate new and ‘controlled’ haptic environments. Third, therapy robots should ideally possess an ability to continuously estimate subjects’ amount of voluntary control and to regulate assistance accordingly. Ultimately, during recovery subjects would learn from robots, and robots would learn from patients.

References


