Robot-Assisted Arm Trainer for the Passive and Active Practice of Bilateral Forearm and Wrist Movements in Hemiparetic Subjects

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Objective: To determine whether use of a robotic arm trainer for bilateral exercise in daily repetitive training for a 3-week period reduced spasticity and improved motor control in the arm of severely affected, chronic hemiparetic subjects.

Design: Before-after trial.

Setting: Community rehabilitation center in Germany.

Participants: Consecutive sample of 12 chronic hemiparetic patients; minimum stroke interval 6 months; patients could maximally protract the affected shoulder, hold the extended arm, or slightly flex and extend the elbow.

Interventions: Additional daily therapy of 15 minutes with the arm trainer for 3 weeks; the 1 degree of freedom trainer enabled the bilateral passive and active practice of a forearm pronation and supination and wrist dorsiflexion and volarflexion; impedance control guaranteed a smooth movement.

Main Outcome Measures: Patients’ impressions, the Modified Ashworth Scale (MAS) score (range, 0–5) to assess spasticity, and the arm section of the Rivermead Motor Assessment (RMA) score (range, 0–15) to assess motor control were rated before therapy, after each 3-week interval, and at follow-up 3 months later.

Results: All patients had favorable impressions: the extremity felt more vivid, and 8 subjects noticed a reduction in spasticity, an ease of hand hygiene, and pain relief. The MAS score of the wrist and fingers joints decreased significantly (P < .0125) from a median of 3 (2–3) and 3 (3–4) to 2 (1–2) and 2.5 (2–3). The RMA score minimally increased in 5 cases without improvement in functional tasks. The median RMA score before therapy was 2.0 (1–2) and 2.0 (1–3.75) after therapy. There were no side effects. At follow-up, the effects had waned.

Conclusions: The arm trainer made possible intensive bilateral elbow and wrist training of severely affected stroke patients. Future studies should address the treatment effect in subacute stroke patients and determine the optimum treatment intensity.

Key Words: Arm; Hemiparesis; Orthotic devices; Rehabilitation; Stroke.

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THE RESTORATION OF ARM and hand function after stroke has a major role in neurorehabilitation. An early, intensive, and task-specific approach is an accepted principle of upper-limb motor rehabilitation. Contraint-induced movement therapy, as measured by the Wolf Motor Function Test (WMFT) and the Motor Activity Log,1 is especially effective in mildly affected patients.

Immobilizing the nonaffected arm, however, is not effective with severely affected patients,2 and, in fact, no arm rehabilitation therapy has proven superior.3 To overcome this problem, our group decided to design and construct a low cost, robot-assisted arm trainer for autonomous, standardized, repetitive therapy.

In the early 1990s, Hogan et al.4-6 developed a robotic arm (MIT-Manus) that made possible unrestricted unilateral passive and active shoulder and elbow movements in the horizontal plane. The robot has been effective in several prospective, randomized clinical studies. Recently, Volpe et al7 summarized the data of 96 subacute hemiparetic patients who were trained either by a robot or by conventional methods. The robot-trained group (1h/d for 5d/wk for 5wk) showed improved performance on the FIM™ instrument and on the Fugl-Meyer arm section and the motor power score for the shoulder and elbow. With the exception of the Fugl-Meyer score, the gains were maintained at 6 months. The subjects were on the average 22 days poststroke.

Further, Burgar et al8 presented the mirror-image motion enabler (MIME), consisting of a robot moving actively or passively the affected arm that was supported by a wristforearm orthosis. Motions of the nonaffected forearm, which was attached to a 6-axis digitizer, commanded the mirror-image movement by the robot, thus enabling the subject to practice bimanual shoulder and elbow movements in the horizontal movement. Daily therapy with the MIME in 21 chronic, moderately affected, hemiparetic subjects resulted in a significant improvement in strength of the biceps, triceps, and deltoideus muscles, and in the elbow and shoulder section of the Fugl-Meyer score in the robot group.8 A precursor version, reported by Lum et al.9 was a robotic assist device for the bimanual practice of wrist flexion and extension. The robotic aid could substitute completely for 1 hand in a bimanual task, as was shown in healthy subjects. Clinical data were not reported.9

Following the bilateral approach, we designed our robot to be a portable version that would enable the bimanual passive and active practice of a 1 degree of freedom (df) forearm and wrist movement, namely, forearm pronation and supination and...
wrist flexion and extension. These more distal movements are an integral part of many daily activities, such as drinking and eating. Further, gentle passive movements of the joints, aimed at muscle tone reduction, and active wrist movements of the paretic side, proved more effective than conventional treatment in the restoration of upper-limb motor function in subacute stroke survivors.\(^\text{10}\) We present here the requested profile and its theoretical basis, the device itself, and our first clinical experiences with chronic, severely affected hemiparetic patients. We selected this population to minimize the influence of any confounding effects of spontaneous recovery.

**METHODS**

**Device Demands and Its Background**

The arm trainer was designed to allow the bimanual practice of arm movement of the impaired arm, as well as dorsiflexion and volarflexion of the wrist. The exercises were to be performed passively or actively (according to the patient’s individual efforts) against an adjustable resistance from the side. The movements were to be regular and undisturbed, which made necessary the impedance control with online force and position registration.

Three operational modes were programmed: (1) a passive mode with speed and range of motion (ROM) individually adjustable; (2) an active mode with the nonaffected arm moving the paretic extremity in a mirror-like fashion; and (3) an active mode as in 2, but the paretic arm had to overcome an individually set, initially isometric resistance to allow the bilateral movement.

These operational modes were based on the following assumptions.

**Passive mode with adjustable speed and ROM.** Smooth passive movements without abrupt tips are accepted mobilization techniques, for instance, within the neurodevelopmental technique (NDT) concept, to improve joint, muscle, and tendon mobility while at the same time reducing muscle tone.\(^\text{11}\) Furthermore, Weiler et al\(^\text{12}\) showed that a passive and active hand movement of healthy subjects resulted in a similar activation of the corresponding sensorimotor cortical area.

Bimanual practice. Bimanual practice has a facilitatory effect on the affected extremity. The consensual operation of the nonaffected upper limb may stimulate ipsilateral corticospinal projections to the paretic muscles, which are regarded as relevant for recovery from hemiplegia. Correspondingly, functional imaging studies after stroke revealed an enhanced activation or blood flow of the ipsilateral sensorimotor area and subsequent motor recovery of the affected extremity.\(^\text{13}\) The MIME robot (see earlier) applied this principle. Further, Mudie and Matyas\(^\text{14}\) compared uni- and bilateral active practicing of daily tasks (e.g., drinking out of a glass) in mildly affected hemiparetic patients (17 wk poststroke) with the help of a multiple baseline-treatment design. Bilateral practice resulted in a recovery of all components assessed, but not in relevant functional use of the arm. More recently, Whithall et al\(^\text{15}\) reported on 14 chronic hemiparetic subjects with antigravity shoulder functions who practiced active bilateral shoulder and elbow movements with rhythmic auditory cueing on a custom-designed machine for four 5-minute periods per session, 3 times a week for 6 weeks. The patients showed significant and potentially durable increases in the following: Fugl-Meyer Assessment, WMFT, and University of Maryland Arm Questionnaire. Further, the isometric strength of wrist and elbow muscles, and the active and passive range of shoulder extension, wrist flexion, and thumb opposition improved.

**Repetitive, active practicing of single distal wrist movements.** Bütefisch et al\(^\text{16}\) investigated hemiparetic patients who were on an average 8.5 weeks poststroke and who had minimal selective finger function in the affected hand. The results of the baseline treatment study showed that an additional repetitive, voluntary dorsiflexion of the affected wrist not only improved direct biomechanic parameters (grip strength, isometric extension force, rapid isotonic wrist extension on an accelerometer), but it also improved the upper extremity’s overall motor function, as assessed with the arm section of the Rivermead Motor Assessment (RMA).

**Therapy of neglect syndrome.** Robertson\(^\text{17}\) pointed out that the repetitive activation of the neglected upper extremity after stroke was superior to frequent visual or acoustic stimuli that attracts attention to the unattended side with respect to improving a neglect syndrome.

**The Arm Trainer**

The subjects sat at a table with their elbows bent 90° and put their forearms in the midposition between pronation and supination into an arm trough. Each hand grasped a handle that was 3 cm in diameter and tapered at the top for ease in inserting into the paretic hand. The hand was held in place by a 6 cm strap with Velcro\(^\text{18}\) (figs 1, 2). The handles were connected by an axis linked to the respective electric motor. Two handle sets were available: 1 with a horizontal axis of rotation for the elbow and 1 with a vertical axis for the wrist movement. To switch movement direction (e.g., from elbow to the wrist movement pattern), the device was tilted 90° downward and the handles exchanged.

The drives provided torques of up to 5 Nm. A position control and the retractive forces of the drive regulated the online registration of position and strength. A computer collected the data and controlled the drives. A display showed the number of performed cycles. A digital control unit positioned between the 2 handles helped to select the operational mode, side of hemiparesis, range, speed, and the resistance of movements. The digital device (800×320×220 mm) could be fixed on any table, ideally on a height- and slope-adjustable therapy table to allow an optimal positioning of the patient. A power supply of 230 V was necessary. Implemented safety features met European standards for medical devices, mainly electro-

![Fig 1. Computer-assisted arm trainer; patient with left hemiparesis practices a repetitive bilateral pronation and supination movement of the forearm.](image-url)
magnetic testing, leaking currents of less than 1mA, a mechanical breaking of the movement when the torques exceeded 4Nm, emergency breaks in the reach of the patients, skin-friendly materials, and minimal risk for contusions. To prevent therapy-related side effects, the total number of repetitions of each movement was limited to 250 per session. In a preceding pilot study, 2 of 10 patients had experienced swollen hands, and in 1 case, there was an activated rhizarthrosis after a more intense therapy with up to 400 repetitions per modus. One repetition of each movement pattern included both movement directions, that is, pronation and supination of the forearm or wrist flexion and extension, respectively.

Patients

Twelve hemiparetic patients participated in an open clinical study approved by the local ethics committee. Inclusion criteria were first supratentorial ischemic stroke with an interval of at least 6 months poststroke; severe upper-arm paresis, that is, the patients could only protract their paretic shoulder girdle, hold their extended arm while lying or prone, and extend their elbow slightly; at least moderate upper-limb flexor spasticity on the affected side; mild or no impairment of sensation of the affected upper extremity, tested for touch, pain as prothopatic and position sense, and dermolexia as epicritic modalities; no additional orthopedic disease (eg, arthritis, arthrosis) of both affected upper extremity, tested for touch, pain as prothopatic and position sense, and dermolexia as epicritic modalities; no additional orthopedic disease (eg, arthritis, arthrosis) of both upper extremities; no neurolytic treatment of spasticity 3 months before or during the study; no severe impairment of cognition and communication (patients had to be able to understand the purpose of the study); and written informed consent.

Participants included 8 men and 4 women with a mean age of 63.6 years (range, 36–78y). The mean stroke interval was 9.3 months (range, 6.0–16mo). Seven subjects had right hemiparesis and 5 had left hemiparesis. Mild sensory impairment was apparent in 5 cases, with prothopatic deficits in 2 and epicritic deficits in 3 cases. The line-cancellation test detected a residual chronic neglect syndrome in 3 cases. All patients participated in a comprehensive inpatient rehabilitation program of at least 4 weeks.

Five patients could only protract the affected shoulder, 5 patients could also hold their extended arm while prone, and 2 subjects could flex and extend their affected elbow for at least 20°. Spasticity ranged from a slight increase to a considerable increase in muscle tone, with passive movement difficult.

Interventions

Patients received a 15-minute net treatment with the arm trainer every workday for 3 weeks, equaling 15 sessions, in addition to participating in the ongoing comprehensive rehabilitation program that included individual physiotherapy and occupational therapy for 45 minutes Monday through Friday. The occupational therapists treated the paretic upper extremities, following the NDT protocol of our department. This included the application of tone-inhibiting maneuvers; gentle mobilization of the shoulder girdle, elbow, wrist, and finger joints; and the facilitation of movements, if possible, from proximal to distal by tapping or weighting down the extended arm. Upper-limb splints or orthoses were not worn.

Assessment and Data Analysis

Two independent raters, 1 physician and 1 occupational therapist not involved in the therapy, tested the patients after each of the 3-week intervals and at follow-up 3 months later. The assessments were done at least 3 hours after a treatment session; for follow-up assessments, patients came to the clinic. The arm section of the RMA served to assess motor control of the affected upper extremity. The section includes 15 motor tasks in a hierarchical order, such as protracting the shoulder girdle, holding the extended arm, and flexion and extension of the elbow while prone, forearm pronation and supination, reaching forward and picking up a large ball with both hands, picking up a tennis ball, a pencil, and a piece of paper with the affected extremity, using cutlery, patting a large ball, and showing various fine motor skills. The most difficult task was to pat-a-cake 7 times in 15 seconds. By using the Modified Ashworth Scale (MAS), we assessed elbow, wrist, and finger spasticity.

Table 1: MAS for Grading Spasticity

<table>
<thead>
<tr>
<th>Grade</th>
<th>Description</th>
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<tbody>
<tr>
<td>0</td>
<td>No increase in muscle tone</td>
</tr>
<tr>
<td>1</td>
<td>Slight increase in muscle tone, manifested by a catch and release, or by minimal resistance at the end of the ROM when the affected part(s) is moved in flexion or extension</td>
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<tr>
<td>2</td>
<td>Slight increase in muscle tone, manifested by a catch, followed by minimal resistance throughout the remainder (less than half) of the ROM</td>
</tr>
<tr>
<td>3</td>
<td>More marked increase in muscle tone through most of ROM, but affected part(s) easily moved</td>
</tr>
<tr>
<td>4</td>
<td>Considerable increase in muscle tone, passive movement difficult</td>
</tr>
<tr>
<td>5</td>
<td>Affected part(s) rigid in flexion or extension</td>
</tr>
</tbody>
</table>

spasticity (table 1). With the patient prone, passive extension of the elbow, wrist, and metacarpal finger joints were tested and rated from 0 (no increase) to 5 (rigid in flexion).19 Interrater reliability was above 0.9 for the RMA and was .82 for the MAS.

Data of the ordinal scales were presented as median and interquartile ranges (IQRs); any within-group differences before and after therapy were calculated with the help of a nonparametric Wilcoxon test. The corrected fore and after therapy were calculated with the help of a interquartile ranges (IQRs); any within-group differences be-
four groups.

Patients rated their subjective impressions by completing a standardized questionnaire at the end of therapy. It asked their impressions of the effects (immediate or lasting) of treatment on muscle tone, on motor control (according to the items of the RMA that are routinely practiced within an occupational therapy [OT] session), competence with the upper extremities in daily activities, and their overall impressions. Ratings were done with a visual analog scale (VAS) on which 0% equaled total unhappiness and 100% equaled total happiness with the arm trainer therapy. A lasting effect on muscle tone was assumed when it continued for at least 3 hours after treatment.

RESULTS

Therapy

Within 1 treatment session, the bilateral passive movement of the forearm and of the wrist were practiced 125 times each (mode 1), followed by 75 repetitions of each movement in mode 2. After a median of 7 days (range, 3–12), 7 patients could also practice the elbow movement up to 50 times in mode 3. Mode 3 was tested with minimal resistance at the end of each session and was continued if the patients could perform at least 10 cycles. For the wrist movement, only 2 patients managed to practice 50 times in mode 3 (one after 7 treatment sessions, the other after 9 treatment sessions). One therapist observed the treatment sessions and helped patients with severe finger flexor spasticity to grasp the handle and close the laces. The patients were instructed to operate the device themselves (setting the individual ROM, choosing the mode, setting the speed, resisting the movements). All but 4 patients learned to do so after a median of 5 sessions (range, 2–8). The therapist ensured that the resistance selected by the patients matched their abilities, and that the patients practiced the chosen movement without accompanying shoulder or elbow movements. This could not be prevented in all cases, particularly at the beginning of the study, but occurred less frequently as the study progressed. There were no device- or therapy-related side effects.

Subjective Impression

Patients’ impressions of the therapy were positive, scoring a mean value of 78.6%±9.8% on the VAS. They reported that the paretic extremity felt livelier, and they noticed an immediate muscle tone reduction of the wrist and finger joints, particularly in the passive operational modus. Eight patients reported an effect on muscle tone that lasted at least 3 hours after a treatment ended, with that time becoming substantially longer during the study. At the study’s conclusion, all 8 subjects reported that muscle tone reduction lasted all day, with sudden increases during stress becoming less pronounced. Consequently, the need for therapeutic joint mobilization within OT and hand hygiene diminished, and spasticity-related pain decreased. Five patients reported better muscle control in that they could now flex and extend their elbow to a larger extent. Three patients also noticed a beginning pronation and supination of the forearm, and 1 patient could actively extend the wrist and finger joints to some extent when treatment ended. Functional motor gains, however, were not reported. At follow-up, effects on muscle tone had waned in 8 of the 12 patients, whereas the functional gains remained constant in 3 of the 5 patients.

Quantitative Data

Assessment of the data (table 2, figs 3, 4) confirmed the subjects’ impression. The MAS scores (range, 0–5) of the affected wrist and finger joints (initial median values, 3.0 [2–3], 0 [3–4]) decreased continuously, resulting in a median value of 2.0 (1–2) and 2.5 (2–3) at the end of the therapy. These changes were significant, with \( P \) equal to .009 and \( P \) equal to .01, respectively. The elbow joint spasticity did not change considerably.

The RMA scores remained constant in 7 patients who had initial and terminal scores of either 1 (5 cases) or 2 (2 cases). The 5 patients who improved their volitional motor function had initial values of 2 (3 cases) or 3 (2 cases); their scores increased.

### Table 2: Clinical Data and RMA Arm Section Score and MAS

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<tbody>
<tr>
<td>1</td>
<td>36</td>
<td>F</td>
<td>Left</td>
<td>1-1-1-1-1-1</td>
<td>4-4-4-4-4</td>
<td>4-3-2-2-3</td>
<td>4-3-2-2-3</td>
</tr>
<tr>
<td>2</td>
<td>78</td>
<td>M</td>
<td>Right</td>
<td>2-2-3-4-4</td>
<td>3-3-3-3-3</td>
<td>3-2-2-1-2</td>
<td>4-3-2-2-2</td>
</tr>
<tr>
<td>3</td>
<td>66</td>
<td>M</td>
<td>Right</td>
<td>1-1-1-1-1</td>
<td>1-1-1-1-1</td>
<td>1-1-1-1-2</td>
<td>2-1-1-1-2</td>
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<tr>
<td>4</td>
<td>69</td>
<td>M</td>
<td>Left</td>
<td>3-3-3-4-4</td>
<td>2-2-2-2-2</td>
<td>2-2-2-2-2</td>
<td>3-3-3-3-3</td>
</tr>
<tr>
<td>5</td>
<td>71</td>
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<td>Left</td>
<td>3-4-4-5-4</td>
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</tr>
<tr>
<td>6</td>
<td>55</td>
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<td>Left</td>
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<td>4-3-2-2-2</td>
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<td>7</td>
<td>69</td>
<td>M</td>
<td>Right</td>
<td>3-3-3-3-3</td>
<td>3-3-3-3-3</td>
<td>4-2-2-2-3</td>
<td>5-4-3-3-3</td>
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<td>9</td>
<td>48</td>
<td>M</td>
<td>Right</td>
<td>2-2-3-3-3</td>
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<tr>
<td>10</td>
<td>61</td>
<td>F</td>
<td>Right</td>
<td>2-2-2-3-2</td>
<td>3-3-3-3-3</td>
<td>3-2-2-2-2</td>
<td>3-3-3-3-3</td>
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<tr>
<td>11</td>
<td>62</td>
<td>M</td>
<td>Left</td>
<td>2-2-2-2-2</td>
<td>3-3-3-3-3</td>
<td>2-1-1-1-2</td>
<td>3-2-2-2-2</td>
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<tr>
<td>12</td>
<td>70</td>
<td>M</td>
<td>Right</td>
<td>1-1-1-1-1</td>
<td>2-2-2-3-2</td>
<td>1-1-1-1-2</td>
<td>3-3-3-3-3</td>
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<tr>
<td>Median</td>
<td>63.6</td>
<td>—</td>
<td>—</td>
<td>2-2-2-2-2</td>
<td>3-2-2-2-2</td>
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<td>3-3-3-3-3</td>
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<tr>
<td>IQR</td>
<td>12-9</td>
<td>—</td>
<td>—</td>
<td>(1-2)-(1-2)-(1-3)-(2-3)-(2-3)-(2-3)-(2-3)-(1-3,75)-(1-3,75)</td>
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Abbreviations: F, female; M, male.
improved 1 (3 cases) or 2 points (2 cases) to values of 3 (2 cases), 4 (2 cases), and even 5 (1 case). In the latter case, the patient could hold a large ball with both hands. The initial and terminal median RMA scores were 2.0 (1–2) and 2.0 (1–3.75). These changes did not reach the selected α value.

At follow-up, the spasticity had almost reached pretherapy levels (ie, the tone-inhibiting effects had waned). The improvement in the RMA was preserved in 3 of the 5 patients, resulting in an overall median of 2 (1–3.75).

**DISCUSSION**

The portable, 1 df robot-assisted arm trainer enabled the bilateral passive and active practice of 2 movements: elbow pronation and supination and wrist dorsiflexion and volarflexion. Three weeks of daily 15-minute practice with the arm trainer resulted in a sustained reduction of muscle tone in 8 of the 12 subjects who had at least a moderate increase in muscle tone before the study. Motor functions improved in 5 subjects without that improvement translating into the performance of functional daily activities. Patients gave the robot-assisted therapy a positive rating; they reported that their upper extremity felt more lively and the sustained muscle tone reduction, and they also stated that the therapy eased hand hygiene and relieved spasticity-related pain. At follow-up, the effects had waned.

How do our results compare with those of other studies on robot-assisted arm training? In the MIT-Manus studies, the robot-trained group of severely affected patients showed a significantly better improvement in the motor power scores and also in the FIM and the Fugl-Meyer arm section scores than did the control group. This convincing result of improved competence in daily activities and motor performance in the robot-group is superior to our results with respect to effectiveness and evidence of data. On the other hand, Volpe et al concentrated on stroke subjects at an early stage after disease onset, as compared with the chronic stroke survivors with poor motor prognosis that we studied.

Burgar et al investigated use of the MIME device in a chronic hemiparetic stroke sample with a mean interval of approximately 26 months between stroke onset and the start of the study. Daily therapy with the MIME resulted in a significant improvement in strength of the biceps, triceps, and deltoideus muscles, and in the elbow and shoulder section of the Fugl-Meyer score in the robot group. The favorable results of improved strength and motor control suggested the superiority of their robot approach. But the MIME patients may have been less affected with a mean Fugl-Meyer score (range, 0–66) of 24.8 before study onset. Our patients, who had no volitional control of forearm, wrist, and finger muscles, may have barely reached this Fugl-Meyer level, although a direct comparison between the RMA and the Fugl-Meyer is difficult.

Technically, both the MIT-Manus and the MIME device are more sophisticated, enabling an unrestricted 2-df shoulder and elbow movement in the horizontal plane instead of a 1-df movement. Given the complexity of human upper-limb motion, the practice of a 2-df movement should prove superior to a 1-df movement. On the other hand, the training of distal rather than proximal movements may have advantages, given the larger cortical representation of distal limb segments. Also, the study of Bütefisch et al may have suggested that the motor recovery of the upper extremity after stroke may spread more effectively from distal to proximal because the active practice of wrist movements was superior to a conventional NDT approach favoring a proximal concept of shoulder trunk alignment.

The major therapeutic effect of the arm trainer was sustained reduction of wrist and finger spasticity and a corresponding ease of hand hygiene and pain relief in 8 of the 12 chronic patients. The initially short effect on muscle tone eventually lasted all day, and sudden stress-related spasticity increases were fewer at the end of therapy. The observed 1-level reduction of the MAS of the wrist and finger joints corresponded to the results reported in several placebo-controlled studies on botulinum toxin—the current major treatment option of focal spasticity. Accordingly, the arm trainer may be an adjunctive tool in spasticity management of severely affected stroke patients, particularly with patients who did not respond to botulinum toxin or could not tolerate the injection procedure.

The major limitation of this open study is the lack of a control group to receive a sham therapy or a conventional treatment. Also, the study does not answer the highly relevant clinical question of whether the arm trainer could accelerate and increase the amount of upper-limb recovery in acute or subacute stroke survivors. Other open questions relate to the optimum therapy intensity, as the daily 15 minutes were less in comparison with the treatment intensity of the MIT-Manus studies, in which patients practiced 1 hour daily, Monday through Friday, for 5 weeks.
CONCLUSION

The newly designed robot-assisted arm trainer may be a viable alternative in the upper-limb rehabilitation of severely affected stroke survivors. It makes possible the early, intensive, and individually adjusted bimanual practice of elbow and hand movement. Structured clinical trials are now needed.

References