

# Effects of Arm Training with the Robotic Device ARMin I in Chronic Stroke: Three Single Cases

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## Key Words

Stroke • Rehabilitation • Recovery of function • Upper extremity • Robotics

## Abstract

**Background:** Several clinical studies on chronic stroke conducted with end-effector-based robots showed improvement of the motor function in the affected arm. Compared to end-effector-based robots, exoskeleton robots provide improved guidance of the human limb and are better suited to train task-oriented movements with a large range of motions. **Objective:** To test whether intensive arm training with the arm exoskeleton ARMin I is feasible with chronic-stroke patients and whether it improves motor function in the paretic arm. **Methods:** Three single cases with chronic hemiparesis resulting from unilateral stroke (at least 14 months after stroke). A-B design with 2 weeks of multiple baseline measurements (A), 8 weeks of training (B) with repetitive measurements and a follow-up measurement 8 weeks after training. The training included shoulder and elbow movements with the robotic rehabilitation device ARMin I. Two subjects had three 1-hour sessions per week and 1 subject received five 1-hour sessions per week. The main outcome

measurement was the upper-limb part of the Fugl-Meyer Assessment (FMA). **Results:** The ARMin training was well tolerated by the patients, and the FMA showed moderate, but significant improvements for all 3 subjects ( $p < 0.05$ ). Most improvements were maintained 8 weeks after discharge. **Conclusions:** This study indicates that intensive training with an arm exoskeleton is feasible with chronic-stroke patients. Moderate improvements were found in all 3 subjects, thus further clinical investigations are justified.

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## Introduction

In Western countries, stroke is the leading cause of disability. Recent studies estimate that stroke affects more than 700,000 individuals in the US alone each year [1]. One major symptom of stroke is acute motor and sensory hemiparesis that affects the upper extremities [2]. Several studies show that sensorimotor arm therapy has positive effects on the rehabilitation progress of stroke patients [3]. The critical factors are that the therapy is *intensive* [4–6], of *long duration* [7], *repetitive*, [8] and *task-oriented* [9–12].

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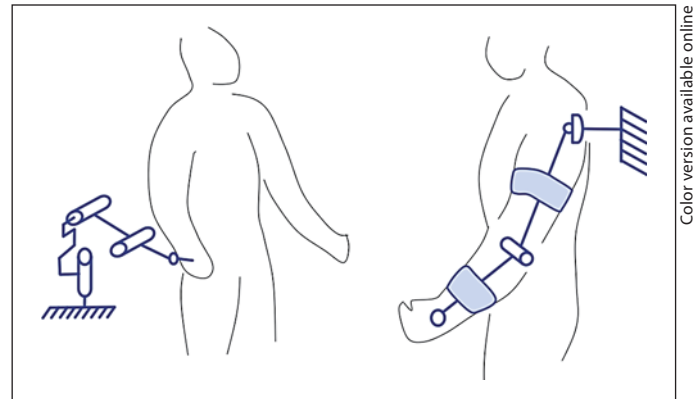
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Regarding these criteria, one-to-one manually assisted training has important limitations. The training is labor-intensive and, therefore, expensive. As a consequence, the rehabilitation period and single training sessions are often shorter than required to achieve maximum therapeutic outcomes. Moreover, manually assisted training lacks repeatability and objective measures of patient performance and progress.

Some shortcomings can be overcome with robots that automate part of the training sessions and allow increasing the number and duration of the training sessions. Furthermore, so-called patient-cooperative control strategies allow patient-driven movements supported by the robot only as much as needed [13]. These control strategies are combined with game-like graphical training scenarios to maximize the patient's motivation and the training intensity [14]. While all existing therapy robots [see ref. 15, 17, 25 for reviews] allow repetitive training, state-of-the-art actuated robots cannot support *task-oriented* training of activities of daily living (ADL). One reason for this limitation is that these robots do not provide the number of actuated joints and the range of motion (ROM) that is required for most ADL tasks. Activities like eating, drinking and dressing require robots with many actuated joints and with a large ROM [18]. Another reason is that we do not know how much patients will gain from multijoint ADL training compared to other training paradigms [19].

Most existing arm therapy robots are so-called end-effector-based robots (fig. 1), where the human hand or lower arm is connected to the end effector of the robot. Examples of end-effector-based robots are the MIT-MANUS robot [20], the MIME robot [21] and the ACT-3D robot [22]. These devices support hand positioning in the 3D space. Since only one segment of the human limb is connected to the robot (i.e. the hand or the lower arm), the individual joint torques are not independently controllable by the robot.

With respect to this shortcoming, several groups have begun working with exoskeleton robots. Examples are the MGA exoskeleton [23], CADEN-7 [24], and the L-Exos [25]. The mechanical structure of exoskeleton robots resembles the human arm anatomy, and the robot's rotation axes correspond to those of the human arm (fig. 1). Consequently, the human arm can be attached to the exoskeleton at several points. Adaptation to different body sizes is, therefore, more difficult than with end-effector-based systems since each robot link must be adjusted to the length of the patient's arm segment. However, the advantage of exoskeleton robots compared to



**Fig. 1.** The end-effector-based robot (left) is connected to the human hand only. The exoskeleton robot (right) is connected to the upper arm, the lower arm and hand.

end-effector-based ones is that the arm posture is fully determined and the torques applied to each joint of the human arm can be controlled separately. The ability to control the interacting torques separately in each joint is essential, notably when the subject's elbow flexors are spastic. Consequently, exoskeleton robots are able to support movements with larger ROM, and, therefore, these robots are generally better suited for ADL tasks.

Several clinical studies have been conducted with end-effector-based robots and they show good results in chronic and subacute stroke [see ref. 26 for a review]. However, no clinical results from studies with active exoskeleton robots have been reported yet. This paper attempts to address this issue. The underlying hypothesis is that the effects of functional, *task-oriented* training [9–12] are superior to the training of nonfunctional artificial movements. Therefore, we hypothesize that the outcome of ADL-oriented training with exoskeleton robots will be superior to the outcome of state-of-the-art end-effector-based robots.

This hypothesis is supported by encouraging results from clinical studies with passive (nonmotorized), non-robotic exoskeletons. One such device, T-WREX [27], is an instrumented exoskeleton that is equipped with springs and allows the training of ADL tasks in a gravity-reduced environment. Sensors measure the actual position and orientation of the human arm which is mapped to a virtual dummy arm on a graphical display that presents the actual task to the patient. A randomized controlled clinical trial [28] demonstrated that exercising the affected arm of 14-month chronic-stroke survivors

using T-WREX for 24 h for an 8-week period improved unassisted movement ability – mean change in the Fugl-Meyer Assessment (FMA) score was 3.6 points  $\pm$  3.9 (mean  $\pm$  SD).

Compared to motorized robots, nonmotorized devices are intrinsically safer, easier to manipulate and handle, and less expensive [29]. Due to their lower inertia, nonmotorized devices are better suited to train very fast or ballistic movements. One obvious disadvantage is that these devices support the human limb against gravity only. This means that directed movements toward an object and joint movements such as elbow extensions and others cannot be assisted by the devices. Most motorized devices can simulate passive behavior, increase the level of difficulty by providing resistance against a user-driven motion and assist the patient in his or her movement. Since severely affected patients need a lot of assistance and well-functioning patients might benefit from resistance, we expect that the effects of training with motorized devices will be superior to training with nonmotorized devices.

This is a pilot study to test the feasibility of using the ARMin I robot as a rehabilitation tool for improving arm function in chronic-stroke victims. The specific hypotheses that are tested in this study are: (1) intensive arm training with the arm exoskeleton ARMin I is feasible with chronic-stroke patients and (2) repetitive and intensive arm training with ARMin I for a 2-month period will improve the motor performance of the affected arm as expressed by the FMA score [26].

## Participants and Methods

### Participants

The study was approved by the local ethics review board. Only chronic-stroke patients were included in order to minimize side effects from spontaneous recovery. Patients were *included* in this study if they fulfilled all of the following criteria: 18–70 years of age, with a first-ever ischemic stroke that occurred at least 12 months prior to the study, termination of conventional therapy and stable recovery stage (outpatients) with moderate to severe motor impairment of the arm (upper limb portion of the FMA score between 10 and 38), able to sit in a chair without any additional support, and written informed consent. Patients were *excluded* from this study if they fulfilled one of the following criteria: excessive spasticity of the affected arm (modified Ashworth Scale  $>4$ ); any serious medical or psychiatric illness; participation in any clinical investigation within 4 weeks prior to the start of this study; an anticipated need for major surgery during the study; women known to be pregnant or lactating; orthopedic, rheumatologic, or other disease that restricts movements of the paralyzed upper extremity; shoulder subluxation (palpatory  $>2$  fingers); diseased or damaged skin at the paralyzed arm; inability to com-

municate effectively with the neurological examiner; serious cognitive deficits (Mini Mental State Exam score  $\leq 21$ ); aphasia preventing the performance of the ARMin treatment, or participation in any treatment performed with the paralyzed arm during the planned study.

Based on the inclusion/exclusion criteria, 3 patients were selected. On admission, subject 1 was 48 years old, 14 months after stroke. Subject 2 was 65 years old, 40 months after stroke. Subject 3 was 55 years old and 25 months after stroke (table 1).

### Study Design

To investigate possible effects of intensive training with the ARMin I device, 3 single-case studies with an A-B design and multiple baseline measurements were performed. During the baseline phase (A), the functional state of the subjects' impaired upper extremity was recorded 3–4 times within 2 weeks with several measurements (see below). In the subsequent intervention phase (B), intensive arm trainings were performed for 8 weeks. Whereas subjects 1 and 2 received three 1-hour training sessions per week, subject 3 received five 1-hour training sessions per week. Subject 3 had more training sessions per week to investigate whether this single subject will tolerate the increased dosage. Eight weeks after the end of the intervention phase, follow-up measurements were recorded.

### Training Sessions

This study was performed with the ARMin I robot [14]. The device stimulates three senses: *haptics* which is stimulated by the physical interaction between the robot and the human, *vision* by a graphical animation that is presented on a computer monitor in front of the patient, and *hearing* stimulated by sounds from two loudspeakers. The device has an exoskeleton structure that connects to the affected upper arm, the lower arm, and the hand. The robot has four motors to provide shoulder abduction/adduction, shoulder flexion/extension, internal/external shoulder rotation, and elbow flexion/extension. It is equipped with sensors that measure position and interaction torques between the human arm and the robot. This allows the device to work either in robot-driven (passive mobilization) or patient-driven (patient active) control mode. As shown in figure 2, the patient sits in a wheelchair and looks at a computer monitor. Depending on the training mode, the monitor shows one of two graphical animations (fig. 2).

Note that the motor for internal/external shoulder rotation was blocked for this first clinical study and there was no actuation of distal joints. Due to these limitations, it was not possible to train task-oriented movements as suggested before. Therefore, simplified movements with 3 degrees of freedom (DOF) were trained. However, based on the experience with the ARMin I device, future versions will be equipped with more DOF and will allow the suggested training of ADL tasks.

Every 1-hour training session started with 20–30 min of *passive mobilization*. To allow the therapist to select a patient-specific mobilization movement, a teach-and-repeat procedure was used. The therapist first guided the arm together with the robot, while the robot recorded the movement ('teach'). Then, the same movement was repeated by the robot several times ('repeat'). During the teaching procedure, the robot was controlled in a zero impedance (zero resistance) mode; thus, the motors were used to compensate for the robot's weight and the joint friction so that the

**Table 1.** Data of the subjects on admission

	Subject 1	Subject 2	Subject 3
Gender	male	male	female
Age	48	65	55
Handedness (before stroke)	right	right	right
Hemisphere of unilateral stroke	right	right	left
Months after stroke (on admission)	14	40	25
Reflex activity <sup>1</sup>	hyperactive	hyperactive	hyperactive
Sensation <sup>1</sup>	reduced	reduced	reduced
Neglect <sup>1</sup>	slight	slight	slight
BI <sup>2</sup> (0–100)	90	85	90
Mini Mental score <sup>3</sup> (0–30)	29	28	22
FMA(0–66)	14	26	15
Muscle tone <sup>1</sup> (Ashworth Scale) <sup>4</sup> (0–5)			
Pure shoulder flexion and abduction	2	2	1
Elbow flexion	2	2	2
Elbow extension	4	4	4
Wrist extension	4	4	3
Finger extension	4	3	3
Muscle strength <sup>1</sup> (MRC) <sup>5</sup> (0–5)			
Shoulder abduction	2	3	2
Pure shoulder flexion	2	3	2
Transversal shoulder ab-/adduction	4	4	4
Elbow flexion	S <sup>6</sup>	4	4
Elbow extension	S <sup>6</sup>	4	2
Active range of motion <sup>1</sup>			
Impairment in shoulder	severe	moderate	severe
Impairment in elbow	moderate	slight	moderate

<sup>1</sup> On the impaired side of the body.  
<sup>2</sup> BI: 0 = total need for care, 100 = completely independent.  
<sup>3</sup> Mini Mental score: 0 = severe dementia, 30 = no dementia.  
<sup>4</sup> Ashworth Scale: 0 = no spasticity, 5 = severe spasticity.  
<sup>5</sup> MRC = Medical Research Council: 0 = no muscle contraction, 5 = full strength.  
<sup>6</sup> S stands for spasticity. It was noted when a muscle or a muscle group was too spastic to enable determination of strength.

therapist mainly felt only the weight and the resistance of the human arm. Additional visual feedback about the actual position and orientation of the affected arm was provided to the patient via the computer monitor (fig. 2) showing a dummy arm that reflects the position and orientation of the real arm. During passive mobilization, the subjects were instructed to watch the graphical animation. The mobilization pattern included all 3 available DOF, thus shoulder abduction/adduction, shoulder flexion/extension, and elbow flexion/extension.

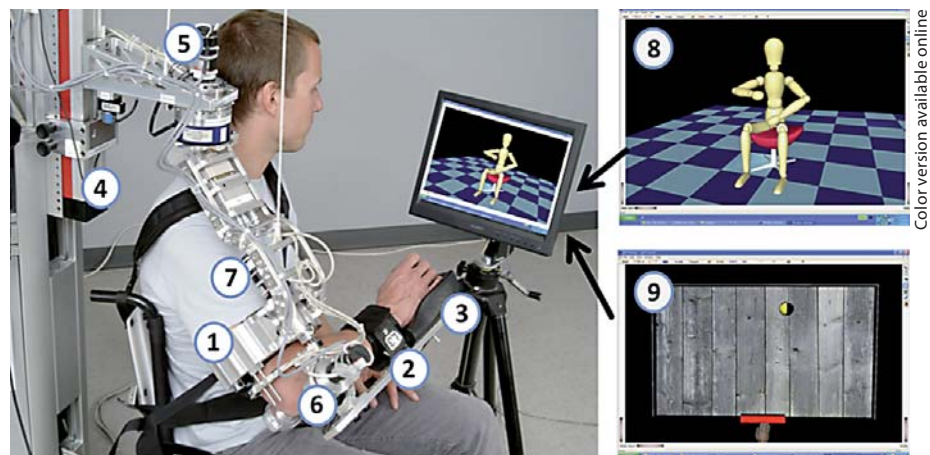
The remaining time of the 1-hour training session was dedicated to *active training*. Subjects tried to catch a ball rolling down a ramp at different locations. The ball was captured and reflected by a handle displayed on the screen. Every capture was accompanied by a sound and after 8 consecutive reflections, a new ball was launched. The position of the handle was controlled by shoulder

and elbow movements. According to the patient's needs, the therapist could select 1 out of 4 different modes (table 2).

In modes 3 and 4, vertical motion of the handle was provided, and subjects could accelerate the ball by hitting it strongly, which added an additional challenge to the training. According to the patient's need, the therapist could vary the level of weight compensation of the arm from 0 to 100%.

During the active training, the robot worked in the user-driven (patient-active) mode (robot impedance controlled). The robot was programmed so that if the subject caught the ball, the robot provided no assistance. Only if the subject was unable to catch the ball would the robot support the patient with an adjustable force and push him or her toward the ball [14]. Since the patients were only supported if they could not catch the ball, the amount of robot support decreased as the patient improved his or her perfor-





**Fig. 2.** Healthy subject sitting in a wheelchair with one arm connected to the ARMin I exoskeleton. The exoskeleton is connected to the human limb via the upper arm cuff (1), the wrist cuff (2), and the hand support (3). The linear drive (4) and the motor (5) power shoulder motion and the motor (6) powers elbow flexion/extension. The motor (7) drives internal/external shoulder rota-

tion and has been disabled for the training. The computer monitor shows screen (8) during the passive mobilization and screen (9) when working in the active training mode. For the sake of clarity, the photo does not show an additional passive linkage that has been used to stabilize the shoulder actuation of the exoskeleton [14].

**Table 2.** Control modes for the active training

	Elbow flexion/extension	Transversal shoulder motion	Shoulder flexion/extension
Mode 1	controls horizontal handle position	blocked	blocked
Mode 2	blocked	controls horizontal handle position	blocked
Mode 3	controls horizontal handle position	blocked	controls vertical handle position
Mode 4	blocked	controls horizontal handle position	controls vertical handle position

mance during the training. To give the subject visual feedback of his or her performance, the color of the handle turned from green to red whenever robot support was delivered.

During the first 3 weeks of the intervention phase, subject 1 spent half of the active training time of each session in training modes 1 and 2. In weeks 4–8, half of the active training time was dedicated to training mode 3 and the other half to training mode 4. The weight compensation of the arm was reduced in a stepwise manner. Subjects 2 and 3 spent about one third of the active training time in training mode 1 and two thirds of their time in training mode 4. The weight compensation of the arm was also reduced stepwise.

#### Outcome Measurements and Data Analysis

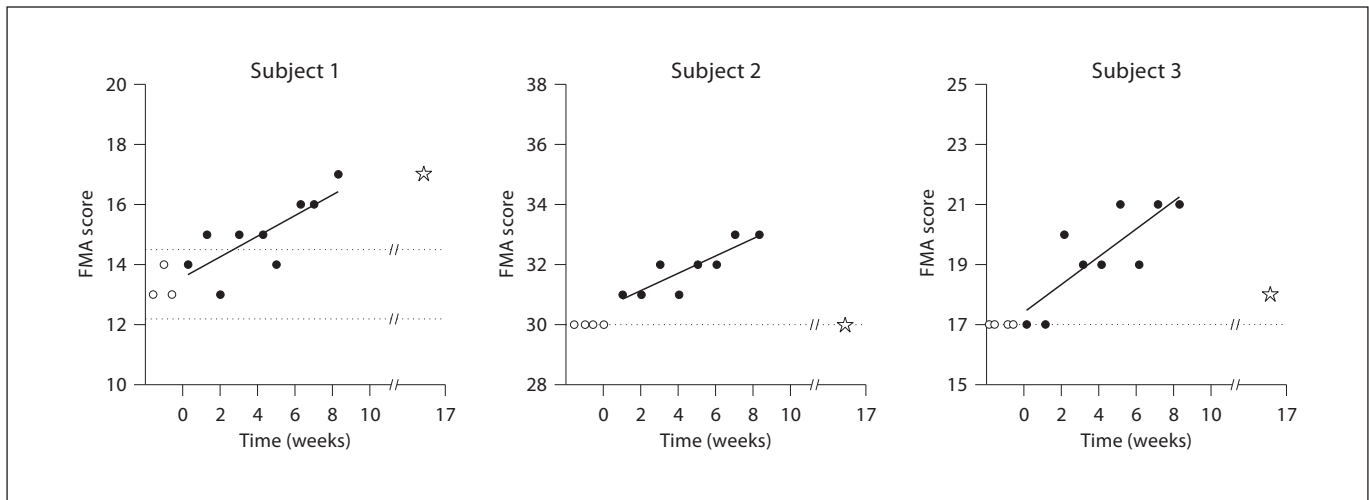
The motor performance of the affected arm was assessed 3 times during the 2-week baseline phase, 9 equally distributed times during the 8-week intervention and once for the 8-week follow-up. It included measurements of function, coordination, range of motion and strength.

The primary outcome measurement was the upper-limb portion of the FMA [30]. In addition to the FMA, to assess the sub-

jects' ability to cope with ADL, the Barthel Index (BI) was used [31]. Furthermore, hand function was assessed by the Action Research Arm Test (ARAT) [32], a series of 19 tasks covering grasp, grip, pinch, and gross arm movements.

The subject's ability to coordinate his or her movements was assessed by a standardized version of the active training that included catching balls that were presented from different locations in a randomized order. The subjects were instructed to match the handle's center mark with the ball reflection point. During this measurement, the robot's support was turned off and the distance between the center mark and the ball reflection point was measured and recorded.

The active range of motion (AROM) in transversal shoulder abduction and elbow flexion and extension was recorded with ARMin. In the starting position, the shoulder was flexed to 70° and transversally abducted to 20°, the rotation was neutral, and the elbow was flexed to 50°. The AROM in shoulder flexion and shoulder abduction was determined using manual goniometry. The strength, i.e. the maximal voluntary muscle torques (MVTs) generated by isometric muscle contraction, was also determined using ARMin. The position (isometric) was the same as for the



**Fig. 3.** FMA scores of subjects 1–3. For every subject, at least 3 baseline values ( $\circ$ ), 8 values during intervention ( $\bullet$ ) and 1 follow-up value are available ( $\star$ ). The solid lines represent the linear regression lines of the data recorded during the intervention phase, and the dotted lines denote the means of the baseline values  $\pm 2$  SDs.

AROM measurement. The tested muscle groups included those responsible for shoulder flexion/abduction (due to the  $20^\circ$  of transversal shoulder abduction in the starting position, both muscle groups were involved), shoulder extension/abduction and transversal shoulder ab- and adduction. The subjects were instructed to maintain their maximal torque for at least 2 s.

To ensure testing consistency, all measurements were executed by the same researcher.

The FMA, AROM and strength measurements were always taken before training. Thus, the measuring conditions were the same during baseline and the intervention phase. To diminish the influence of the learning effect due to the repetitive accomplishment of the measurements, the participants completed two test measurements on different days before onset of the baseline phase. The coordination test was performed after mobilization. Since no mobilization occurred during the baseline phase, the data of the coordination test were collected during the intervention phase only.

The statistical analysis of the FMA, BI, ARAT, AROM and strength data recorded during the baseline phase included the calculation of the means and the standard deviation (SD) of the means. For all data recorded during the intervention phase, linear regression including the standard error (SE) and the p value of the slope of the regression line were calculated. Furthermore, it was analyzed whether the endpoint of the regression line (EPR) was higher than the mean of the baseline data  $+2$  SDs. The linear model of regression was applied because it provides an easy way of quantifying improvements. To interpret the statistical data, slopes of regression lines with a p value of  $\leq 0.2$  were assumed to indicate an increasing/decreasing tendency. If the p value was  $\leq 0.05$ , the increase/decrease was considered statistically significant.

## Results

The FMA of all 3 subjects showed significant improvements (fig. 3). The gains in subjects 1, 2, and 3 were 3.1, 3.0, and 4.2 points, respectively. In percentages of the total score (66 points), the increases were 4.7, 4.6 and 6.4%, respectively. Follow-up measurements showed that subject 1 could maintain the increased level, subject 3 could maintain it to some degree, and subject 2 returned to the baseline level. The ARAT and the BI did not change in any subject (table 3).

All 3 subjects showed improved performance on the coordination test (table 3). Regarding the shoulder movements, subjects 1 and 2 showed statistically significant improvements ( $p \leq 0.05$ ) and subject 3 showed a tendency to improve ( $p \leq 0.2$ ). Regarding the elbow movements, subjects 1 and 3 showed an improving tendency and subject 2 showed significant improvements. In both shoulder and elbow, the improvements were maintained to some degree 8 weeks after the end of the intervention phase (table 3).

Overall, all 3 subjects showed increased AROMs. Regarding transversal shoulder abduction, the EPR was higher than the mean  $\pm 2$  SDs in subjects 2 and 3. The increases were  $13.7$  and  $19.3^\circ$ , respectively. In subject 1, only one baseline value was available, and therefore, the increase from the mean of the baseline to the EPR could not be determined. All subjects could maintain the increased level until follow-up measurements. The im-

**Table 3.** Summary of the results

	Subject 1				follow-up
	baseline mean $\pm$ SD	regression line slope $\pm$ SE	end point	p	
Coordination transversal ab-/adduction	NA	$-0.12 \pm 0.04$	0.6	0.03	0.7
Coordination elbow flexion/extension	NA	$-0.34 \pm 0.16$	0.6	0.09	1.3
Strength shoulder flexion/abduction, Nm	$32.9 \pm 11.5$	$0.02 \pm 0.75$	36.3	0.98	46.0
Strength shoulder extension/adduction, Nm	$40.9 \pm 6.4$	$2.64 \pm 1.08$	45.8	0.05	42.7
Strength transversal abduction, Nm	$14.8 \pm 3.9$	$0.09 \pm 0.27$	17.9	0.76	11.1
Strength transversal adduction, Nm	$8.0 \pm 2.1$	$0.75 \pm 0.38$	18.1	0.09	18.1
AROM shoulder abduction, degrees	$51.3 \pm 11.0$	$1.23 \pm 0.71$	62.0	0.13	60.0
AROM shoulder flexion, degrees	NA	NA	NA	NA	NA
AROM transversal abduction, degrees	NA	$2.56 \pm 1.81$	62.4	0.21	69.4
AROM elbow flexion/extension, degrees	$71.3 \pm 0.7$	$5.53 \pm 1.33$	103.0	$<0.01$	91.8
FMA (0–66)	$13.3 \pm 0.6$	$0.35 \pm 0.11$	16.4	0.02	17.0
ARAT (0–57)	$4.0 \pm 0.0$	$0.04 \pm 0.04$	4.00	0.44	4.00
BI (0–100)	$90.0 \pm 0.0$	$0.00 \pm 0.00$	90.00		90.00

provement in AROM in shoulder abduction was less than  $\pm 2$  SDs of baseline. Subjects 1 and 3 were unable to perform a shoulder flexion without abduction. Therefore, the AROM in shoulder flexion could be determined only in subject 2. These data did not change during the course of the study. Regarding elbow flexion/extension, the data showed a statistically significant increase and the EPRs were higher than the mean  $\pm 2$  SDs in subjects 1 and 3. The increases were 31.7 and 22.5°, respectively, but subject 2 also showed a nonsignificant increase of 9.5°. At follow-up, all subjects maintained the increased level.

In general, all 3 subjects showed increased MVTs. In shoulder flexion, a statistically significant increase was observed in subject 3 and the EPR was higher than the mean  $\pm 2$  SDs (fig. 4). The increase was 23.7 Nm (123%) and was maintained until follow-up. In shoulder extension, the data of subjects 1 and 2 showed a statistically significant increase. However, as the starting point of the regression line was considerably lower than the mean of the baseline, the EPRs were not higher than the means  $\pm 2$  SDs. The values achieved by the end of the intervention phase were maintained until follow-up. The MVTs in transversal shoulder abduction did not increase in subjects 1 and 2. In contrast, in subject 3, there was a statistically significant increase and the EPR was higher than the mean  $\pm 2$  SDs. The increase was 12.8 Nm (133%). Only a small portion of this increase could be maintained until follow-up. In transversal shoulder ad-

duction, the data of subjects 1 and 2 tended to increase. Although the improvements were not statistically significant, the EPRs were higher than the means  $\pm 2$  SDs. The increases were 10.1 (126%) and 11.4 Nm (120%). These increased levels were also reached on the follow-up examinations.

## Discussion

### Results of the ARMin I Study

It is well known that coordination of muscle activation in stroke is impaired due to brain lesions [33–35]. One consequence is the loss of dexterity [36]. Moreover, the number of motor units activated is often decreased [37] and pronounced cocontraction of agonistic and antagonistic muscles can appear [38]. Both these consequences seem to cause muscle weakness in stroke patients. Since intensive training has been shown to induce changes in cortical activation, even in chronic-stroke patients [6, 38], ARMin I training was expected to improve coordination of muscle activation. In turn, improvements in coordination of muscle activation were expected to align with improvements in muscle strength.

The AROM and the FMA were assumed to increase in parallel. Since others have reported that the BI is inconsistent in clinical trials in stroke medicine [39], no expectations about changes were made. This is also the case for the ARAT score, which exclusively tests hand function.

Subject 2					Subject 3				
baseline mean $\pm$ SD	regression line			follow- up	baseline mean $\pm$ SD	regression line			follow- up
	slope $\pm$ SE	end point	p			slope $\pm$ SE	end point	p	
NA	$-42.0 \pm 0.06$	0.7	$<0.01$	1.4	NA	$-0.13 \pm 0.07$	1.3	0.10	1.0
NA	$-0.40 \pm 0.13$	1.0	0.03	2.3	NA	$-0.58 \pm 0.41$	3.7	0.21	3.2
$52.0 \pm 3.0$	$1.44 \pm 1.27$	56.6	0.30	60.0	$19.3 \pm 3.8$	$2.80 \pm 0.76$	43.0	$<0.01$	39.8
$41.0 \pm 5.1$	$2.90 \pm 0.67$	51.2	$<0.01$	49.2	$23.5 \pm 6.6$	$-0.48 \pm 1.13$	29.3	0.68	40.7
$19.0 \pm 1.6$	$0.45 \pm 0.48$	19.3	0.38	19.7	$9.6 \pm 2.3$	$0.89 \pm 0.17$	22.4	$<0.01$	16.9
$9.5 \pm 2.5$	$0.81 \pm 0.47$	20.9	0.14	20.2	$1.9 \pm 2.7$	$-0.10 \pm 0.29$	2.2	0.73	7.4
$95.0 \pm 6.4$	$1.39 \pm 1.05$	98.8	0.24	100.0	$66.0 \pm 10.5$	$0.24 \pm 1.64$	76.5	0.89	80.0
$101.0 \pm 3.5$	$0.46 \pm 1.11$	103.0	0.69	100.0	NA	NA	NA	NA	NA
$67.7 \pm 6.0$	$0.50 \pm 0.44$	81.4	0.30	85.9	$79.2 \pm 3.1$	$1.47 \pm 0.83$	98.5	0.12	98.5
$75.0 \pm 6.3$	$1.08 \pm 0.79$	84.5	0.23	91.9	$78.0 \pm 6.3$	$1.77 \pm 0.28$	100.5	$<0.01$	99.8
$30.0 \pm 0.0$	$0.29 \pm 0.07$	33.0	$<0.01$	30.0	$17.0 \pm 0.0$	$0.46 \pm 0.13$	21.2	$<0.01$	18.0
$13.0 \pm 0.8$	$0.04 \pm 0.25$	14.00	0.88	12.00	$4.5 \pm 0.6$	$0.11 \pm 0.09$	4.80	0.23	4.0
$85.0 \pm 0.0$	$0.00 \pm 0.00$	85.00		85.00	$90.0 \pm 0.0$	$0.00 \pm 0.00$	90.00		90.00

Since hand function was not trained in this trial, no changes were expected.

As expected, subject 1 showed improvements in the coordination test (shoulder and elbow movements) as well as in muscle strength and AROM. An increase in the FMA score was achieved in two tasks of which only one was trained. Therefore, a transfer process may have taken place. In subject 2, the ARMin I training mainly influenced the coordination of shoulder and elbow movements. An improvement in AROM only occurred in transversal shoulder abduction, and this improvement occurred only in the first training week. One possible explanation for this restriction is that the value reached after the first training week corresponded to the maximum angle of the training settings. The increase in the FMA score can mainly be ascribed to the improved ability to purely flex and abduct the shoulder without flexion of the elbow. This finding indicates a slightly reduced dependence on the synergy patterns that are characteristic of stroke patients [40]. In subject 3, improvements were most pronounced. The reason seems to be twofold: this subject had a greater number of training sessions and had a left-hemispheric lesion which is reported to be advantageous for training response in right-handed subjects [34]. Improvements in the FMA score can be correlated to improved shoulder abduction (as part of a complex movement), shoulder flexion and abduction without flexion of the elbow as well as improved ability to put the hand onto the lumbar

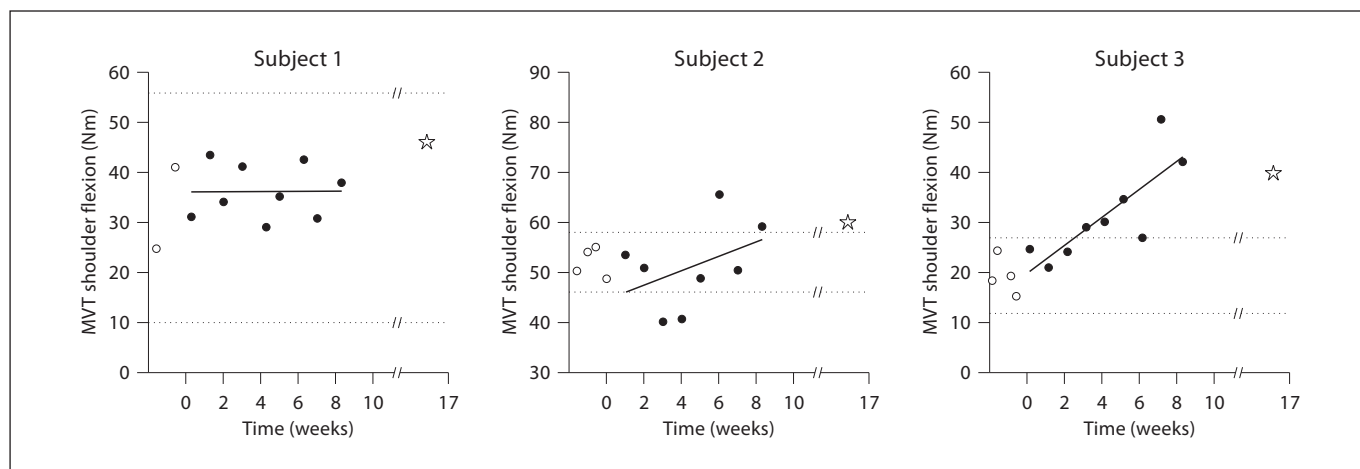
spine. The improvements in shoulder flexion and abduction without flexion of the elbow suggest that, as in subject 2, the dependence on synergy patterns might have been reduced. This matches the findings of Ellis et al. [41], who reported that abnormal joint patterns can be reduced by training.

The relevance of these results to other attempts at automating movement training after stroke will be discussed first, and then directions for future research will be addressed. Since the FMA score is the main outcome measurement of most studies, including the ARMin I study, the comparison with other studies is based on the FMA only.

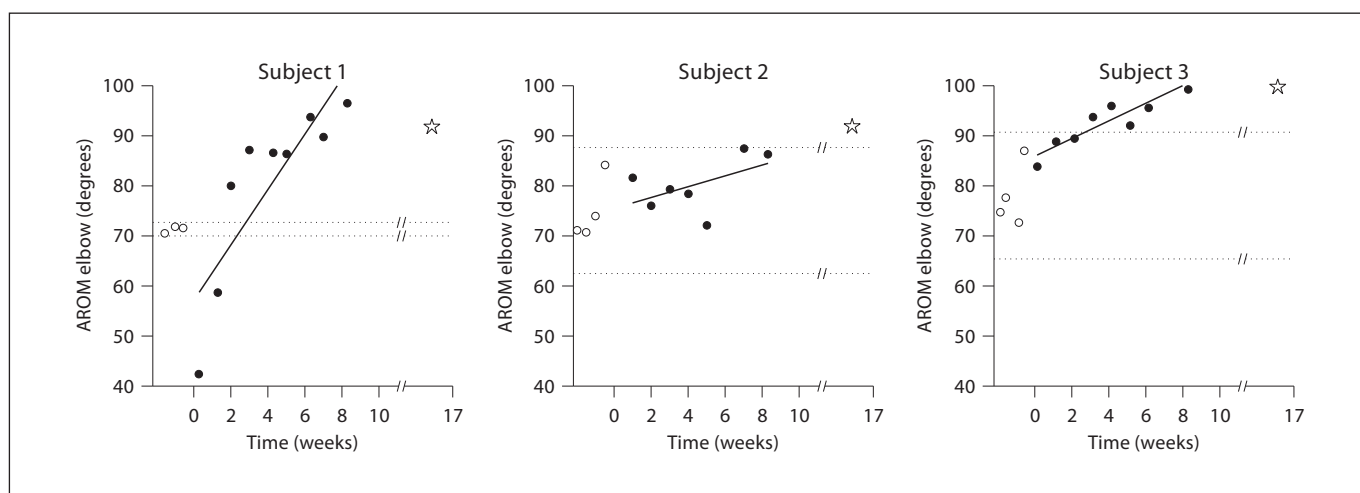
#### *Comparison with Other Robot-Supported Arm Therapy Studies*

In a randomized, blinded and controlled trial including 27 chronic-stroke patients (6 months after stroke), robotic therapy with the end-effector-based robot MIME was compared to conventional neurodevelopmental therapy targeting proximal upper limb function [21]. Both groups received 24 therapy sessions of 1 h each for 2 months. At the end of the intervention, the gains in the FMA scores were  $4.7 \pm 1.2$  points in the robot group versus  $3.1 \pm 0.8$  points in the control group. At the same point in time, in the ARMin I study, gains in the FMA score were 3.1, 3.0 and 4.2 points for subjects 1, 2 and 3.





**Fig. 4.** MVT in shoulder flexion of subjects 1–3. The circles (○) refer to baseline measurements, the dots (●) represent data that were recorded during the intervention phase, and the stars (☆) represent data from follow-up measurements. The solid lines represent the linear regression lines of the data recorded during the intervention phase, and the dotted lines denote the means of the baseline values  $\pm 2$  SDs.



**Fig. 5.** AROM in the elbow flexion/extension of subjects 1–3. The circles (○) refer to baseline measurements, the dots (●) represent data that were recorded during the intervention phase, and the stars (☆) represent data from follow-up measurements. The solid lines represent the linear regression lines of the data recorded during the intervention phase, and the dotted lines denote the means of the baseline values  $\pm 2$  SDs.

In the ARMin I study, subjects 1 and 2 received 24 therapy sessions of 1 h each for 2 months, and subject 3 received 32 therapy sessions of 1 h each for the same duration. Therefore, the beneficial effects of the ARMin I therapy in this study were less pronounced than those in the MIME study. In fact, the effects of the ARMin I study were very similar to those of the control groups of the

MIME study. Note that the protocol of the robotic group in the MIME study included a bimanual mode. In this mode, the two forearms were kept in mirror symmetry by a position digitizer that measured the movement of the contralateral forearm and provided coordination for the robot motion controller of the affected arm. This mode might explain the higher gains in the MIME study.

The improvements observed in the ARMin I study are also comparable to improvements with other end-effector-based devices such as the MIT-MANUS (4.2 additional points on the FMA with the robot therapy) [42] and the GENTLE/s (4-point gain on the FMA with the robot therapy) [43].

A randomized controlled clinical trial [44] with the passive, nonrobotic exoskeleton T-WREX has been carried out with 23 chronic-stroke patients. Subjects with moderate to severe upper-limb hemiparesis were trained 3 times a week for 8 weeks with minimal supervision by occupational therapists. In preliminary results, the T-WREX group demonstrated significant improvements in arm movement (3.7 points mean improvement on the FMA,  $p = 0.001$ ). An important secondary finding of this study was that the training with the arm exoskeleton led to significant gains in self-rated quality of arm movements on the Motor Activity Log ( $p = 0.05$ ).

#### *Interpretation and Directions for Future Research*

This study has aimed to test whether intensive arm training with the arm exoskeleton ARMin I is feasible with chronic-stroke patients (hypothesis 1) and to test whether repetitive and intensive arm training with the ARMin I for a 2-month period will improve motor performance in the affected arm as measured by the FMA score (hypothesis 2). The training was feasible and very much appreciated by the patients. Thus, hypothesis 1 is confirmed by this study. In effect, not a single training session was canceled. Two different dosages were tested: 3 h a week and 5 h a week. Both were well tolerated, and we will continue to deliver these dosages in future studies. The 3 single cases had considerable spasticity, and we observed that the selected training paradigm, starting with 20–30 min passive mobilization, followed by active training, was well suited to these patients. In effect, we observed that passive mobilization seems to reduce spasticity and improve flexibility. These effects will be further investigated in future clinical trials.

Significant improvements in the FMA scores were found in all patients, which is in support of hypothesis 2. Three subjects are not sufficient to definitively prove hypothesis 2, but the data obtained in this study justify a larger-scale randomized clinical trial.

Overall, the mean improvement in the FMA scores in this study (3.4 points) compares well with the results of studies with end-effector-based robots. The study with the MIME robot, in which the mean gains on the FMA were higher (4.7 points), was the only exception. However, we expected that the effects of training with mo-

torized exoskeletons would be superior to training with end-effector-based devices because we believed that exoskeletons were better suited for training task-oriented movements. Since only 3 of the DOF of the ARMin I device were used and ADL movements require at least 6 DOF plus hand-opening and closing [18], the training procedure in this study did not include task-oriented movements. It is, therefore, no surprise that changes in the FMA score are rather small. This is also the reason why the second version of the device, the ARMin II robot, is equipped with 6 DOF, which allow training of task-related movements [45].

The mean gain on the FMA in the T-WREX study (3.7 points) was slightly higher than the mean gain in the ARMin study (3.4 points). The main advantage of the T-WREX is that the device provides movements with 5 DOF plus hand actuation; this enables the training of tasks that are very close to ADL tasks. The ARMin II robot will be able to provide similar exercises with additional motorized support.

#### **Conclusion**

This study examined the effects of intensive arm therapy with the ARMin I robotic device. While most studies on the influence of robotic training have been conducted with end-effector-based robots, the present study has been carried out with an actuated exoskeleton robot. Thanks to a large ROM and enhanced joint guidance, the exoskeleton structure enables the training of ADL-related, task-oriented movements. A simplified version of ARMin with only 3 DOF has been used. Due to the limited number of DOF, only nonfunctional movements could be trained in this study. Nevertheless, the ARMin I served as model for the ARMin II robot, which has 6 DOF and allows ADL training. We expect more pronounced improvements in subjects that undergo ARMin II training.

The present study on 3 single cases has shown that the ARMin I training had positive effects on the coordination of arm movements, functional tasks, AROM, and muscle strength. Most improvements could be maintained 8 weeks after the end of the intervention phase. However, individual subjects did not improve in all parameters and the parameters that did improve differed widely. Therefore, the effects of the ARMin I training seem to be individual and differ among the 3 subjects.

The fact that the improvements did not occur in all movements trained is consistent with the results reported by others. The improvements in the FMA scores are similar to those in studies with end-effector-based robots and passive, nonrobotic exoskeletons. This was the first study on the ARMin I exoskeleton; future studies will be performed with improved versions of the ARMin device and are expected to show better results.

## Acknowledgments

We thank Dr. Tillmann Krüger for performing the physical examinations of the subjects. Special thanks are also extended to Prof. Dr. Volker Dietz, Dr. Ewa Siekierka-Kleiser, Claudia Rudhe-Link and Claudia Rotta, all from Balgrist University Hospital, Zurich, Switzerland, for their assistance. Furthermore, we would like to sincerely thank the subjects who participated in this study.

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