Three-Dimensional Multi-Degree-of-Freedom Arm Therapy Robot (ARMin)

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Abstract

Rehabilitation robots have become an important tool in stroke rehabilitation. Compared to manual arm therapy, robot-supported arm therapy can be more intensive, of longer duration, and more repetitive. Therefore, robots have the potential to improve the rehabilitation process in stroke patients. In this chapter, the three-dimensional, multi-degree-of-freedom ARMin arm robot is presented. The device has an exoskeleton structure that enables the training of activities of daily living. Patient-responsive control strategies assist the patient only as much as needed and stimulate patient activity. This chapter covers the mechanical setup, the therapy modes, and the clinical evaluation of the ARMin robot. It concludes with an outlook on technical developments and about the technology transfer to industry.

Keywords

Exoskeleton • Rehabilitation • Stroke • Upper extremity • Virtual reality

9.1 State of the Art

9.1.1 Rationale for Application of Current Technology

Stroke remains the leading cause of permanent disability. Recent studies estimate that it affects more than one million people in the European Union [1, 2] and more than 0.7 million in the United States each year [3]. The major symptom of stroke is severe sensory and motor hemiparesis of the contralesional side of the body [4]. The degree of recovery depends on the location and the severity of the lesion [5]. However, only 18% of stroke survivors regain full motor function

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after 6 months [6]. Restoration of arm and hand function is essential to resuming daily-living tasks and regaining independence in life. Several studies show that sensorimotor arm therapy has positive effects on the rehabilitation progress of stroke patients [7–9].

The goal is to induce long-term brain plasticity and improve functional outcomes. Relevant factors for successful therapy include training intensity [10–12], duration [13, 14], and repetition [15].

With respect to these criteria, one-to-one manually assisted training has several limitations. It is labor-intensive, time-consuming, and expensive. The disadvantageous consequence is that the training sessions are often shorter than required for an optimal therapeutic outcome. Finally, manually assisted movement training lacks repeatability and objective measures of patient performance and progress.

Some shortcomings can be overcome by the use of robotics. With robot-assisted arm therapy, the number and duration of training sessions can be increased while reducing the number of therapists required per patient. Thus, it is expected that personnel costs can be reduced. Furthermore, robotic devices can provide quantitative measures and support the objective observation and evaluation of the rehabilitation progress.

Fig. 9.1 Typical setup for a robot-supported arm therapy system

9.1.2 Therapeutic Actions and Mechanism

Numerous groups have been working on arm-rehabilitation robots, and several different types of rehabilitation robots have been developed and tested with stroke patients. In this article, we discuss different types of robotic arm therapy by analyzing several arm robots. This is not an exhaustive analysis of arm therapy robots, and the interested reader is referred to appropriate review articles [16–18].

The typical setup for robot-supported arm therapy consists of the seated stroke patient with the most affected arm connected to the robotic device (Fig. 9.1). In most applications, the patient looks at a graphical display – either a large, immersive 3D projection or standard computer screen. The robotic device is characterized by its mechanical structure, the number and type of actuated joints, and the actuation principle. This section discusses these three key characteristics and their influence on the rehabilitation training.

9.1.2.1 Mechanical Structure: End-Effector-Based Robots and Exoskeleton Robots

End-effector-based robots are connected to the patient's hand or forearm at one point (Fig. 9.2). Depending on the number of links of the robot, the human arm can be positioned and/or oriented in space. The robot's axes generally do not correspond with the human-joint rotation axes. That is why, from a mechanical point of view, these robots are easier to build and to use.

Many researchers have developed and evaluated end-effector-based robots. The MIT Manus [19], the Mirror Image Motion Enabler [20], the Bi-Manu-Track [21], the GENTLE/s [22], and the Arm Coordination Training Robot [23] are examples of end-effector-based robotic devices. An important advantage of these robots is that

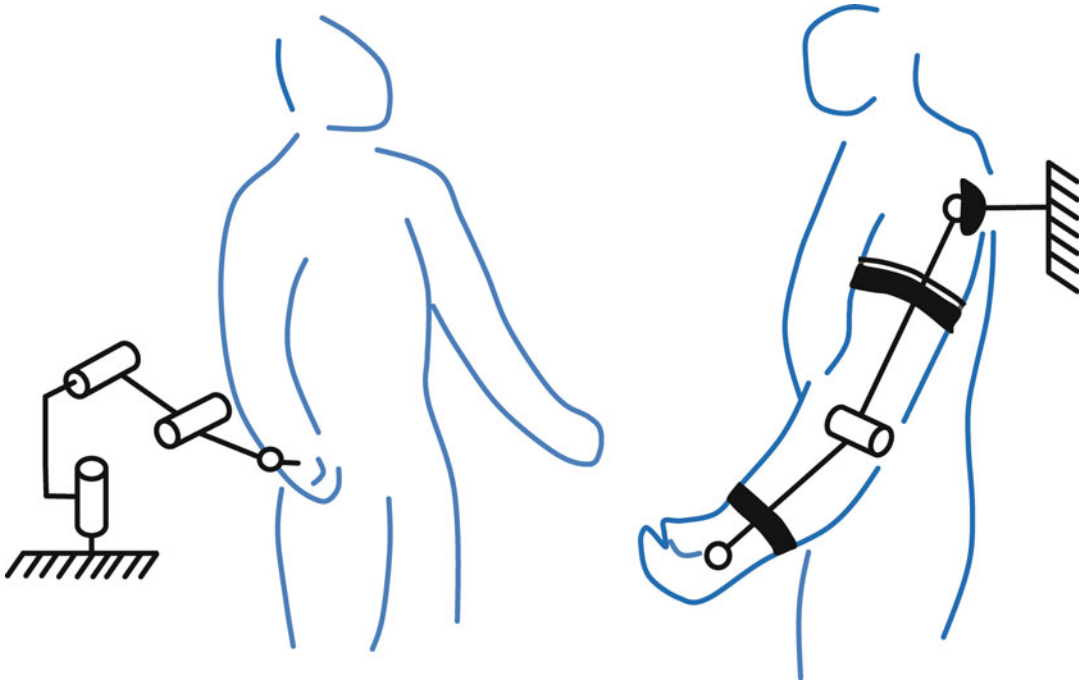

Fig. 9.2 Schematic view of end-effector-based (*left*) and exoskeleton (*right*) robots

they are easy to adjust to different arm lengths. A disadvantage is that, in general, the arm posture and/or the individual joint interaction torques are not fully determined by the robot because the patient and the robot interact just through one point – the robot's end effector.

The mechanical structure of the exoskeleton robot resembles the human arm anatomy, and the robot's links correspond with human joints. Consequently, the human arm can be attached to the exoskeleton at several points. Adaptation to different body sizes is, therefore, more difficult than in end-effector-based systems because the length of each robot segment must be adjusted to the patient's arm length. Since the human shoulder girdle is a complex joint, this is challenging and requires advanced mechanical solutions for the robot's shoulder actuation [24]. However, with an exoskeleton robot, the arm posture is fully determined, and the applied torques to each joint of the human arm can be controlled separately. The ability to separately control the interacting torques in each joint is essential, such as when the subject's elbow flexors are spastic. The mobilization of the elbow joint must not induce reaction torques and forces in the shoulder joint, which can be guaranteed by an exoskeleton robot, but not by an end-effector-based one. That is also why therapists use both hands to mobilize a spastic elbow joint. To avoid exercising forces to the shoulder, one hand holds the lower arm while the other hand holds the upper arm. This is comparable to an exoskeleton robot with a cuff affixed to the lower arm and another cuff affixed to the upper arm. Some examples of arm-rehabilitation exoskeletons include the Dampace [25], the Armeo (former T-Wrex) [26], the MGA-Exoskeleton [27], the L-Exos [28], the Caden-7 [29], the Intelligent Robotic Arm [30], and the ARMin I, II, and III devices [24, 31].

While it seems clear that end-effector-based robots have practical advantages (usability, simplicity, and cost-effectiveness) and exoskeleton robots have biomechanical advantages (better guidance), it remains an open research question whether and how this disparity influences therapeutic outcomes.

9.1.2.2 Number and Type of Actuated Joints

The number and type of actuated joints is another point of differentiation among robotic devices. Some groups focus on a functional training that includes the entire arm and hand (proximal and distal joints). This functional training can be based on activities of daily living (ADL) and requires sophisticated and complex robotic devices such as the GENTLE/s, the Dampace, the Armeo Spring, or the ARMin robot. The reason for ADL training is that there is evidence that functional and task-oriented training shows good results in stroke patients [9, 32]. This confirms previous observations made with the constraint-induced movement therapy. Intervention studies have shown that forcing the affected limb to perform ADLs yields functional gains, allowing the stroke patient to increase the use of the affected arm in the "real-world" environment [33–36].

Other groups have developed robots that focus on the training of distal parts of the human arm such as the hand [37], the wrist, and the lower arm [38, 39]. One may speculate that the distal approach results in a more powerful activation of the sensorimotor cortex, given their larger cortical representation [40]. The recently suggested competition between proximal and distal arm segments for plastic brain territory after stroke [41] would imply shifting treatment emphasis from the shoulder to the forearm, hand, and fingers. Other devices work more proximal on the elbow and shoulder [23, 42]. Namely, the Act3D robot implements an impairment-based, 3D robotic intervention that specifically targets abnormal joint torque coupling between the elbow and shoulder joint [43].

The research question is whether robotic training should focus on whole-arm/hand functional movements, only distal, or distal and proximal.

9.1.2.3 Actuation Principle: Nonmotorized Robots and Motorized Robots

Most motorized rehabilitation robots are powered by electric motors. Depending on the underlying control paradigm, the motors can either control the interaction force/torque between the patient and the robot or the position of the robot. This allows the robotic device to support the human arm against gravity, canceling gravitational forces and making it easier for the patient to move his arm. Also, motorized robots can support the patient in movement toward a target, such as an object within an ADL training scenario. If required, electric motors can also resist the patient in the movement, making the patient's arm heavier or making the patient feel that he is carrying an object with a given mass. Motorized robots can be used as an evaluation tool to objectively measure voluntary force, range of motion, and level of spasticity [44, 45]. Another important application is having the robot introduce force fields onto the endpoint of the human. The adaptation of the human to different force fields is expected to trigger plasticity changes in the brain and enhance rehabilitation.

Some recent rehabilitation devices have been developed to work without motors [25, 26]. The commercially available Armeo Spring device is based on the former T-Wrex device [46] and works without any motors. In this exoskeleton device, springs support the human arm against gravity. The mechanical design allows the therapist to adjust the spring length and to select the proper amount of support. Sensors measure the position and orientation of the human arm, which is transmitted to the graphical display where the patient can see his own movement on the computer screen. Compared to motorized robots, this approach has the great advantage of significantly lower costs and weight. Moreover, the device is easier to use and intrinsically safe. The disadvantage is that it is not possible to support the patient other than against gravity, so, for instance, the device cannot support the patient in directed reaching movements, nor can it challenge the patient by resisting movement. Some devices overcome this by adding brakes to the robot that dissipate energy and challenge the patient's movements [25]. Current evidence suggests that nonmotorized devices might be very well suited for the training of mildly impaired stroke patients who do not need as much support as heavily impaired subjects [46].

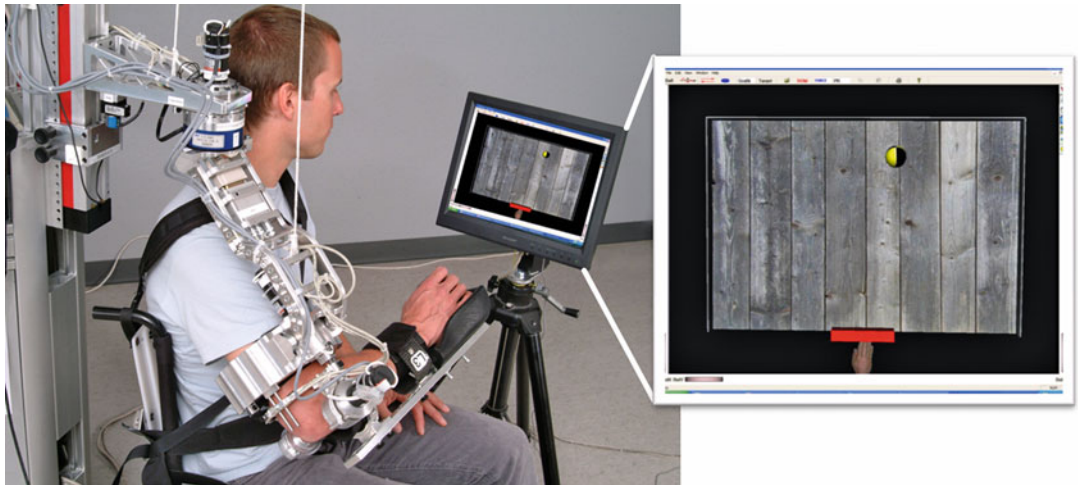

Fig. 9.3 ARMin I robot with a healthy test person (*left*). The person is looking at a computer monitor showing the movement task (*right*)

9.2 Review of Experience and Evidence for the Application of the ARMin Robot System

9.2.1 Technical Evaluation of the ARMin Robot System

The first version of the arm therapy robot, ARMin I, was designed and tested from 2003 to 2006 at the ETH Zurich in close collaboration with therapists and physicians from the University Hospital Balgrist, Zürich [31, 47]. This version is characterized by 4 degrees of freedom actuating the shoulder in 3D and flex/extend the elbow (Fig. 9.3). The upper arm is connected to the robot by an end-effector-based structure. Like later versions of the ARMin, the device could be operated in three modes: passive mobilization, active game-supported arm therapy, and active training of activities of daily living (ADL). The improved version, ARMin II, was characterized by a complete exoskeletal structure with two more degrees of freedom (six altogether) allowing also pronation/supination of the lower arm and wrist flexion/extension (Fig. 9.1). Particular efforts were undertaken to optimize shoulder actuation: a sophisticated coupling mechanism enables the center of rotation of the shoulder to move in a vertical direction when the arm is lifted [48, 49]. This function is required to provide an anatomically correct shoulder movement that avoids shoulder stress from misalignment of the robot and anatomical joint axes when lifting the upper arm above face level.

ARMin III (Fig. 9.4) was further improved with respect to mechanical robustness, complexity, user operation, and reliability [24]. Five ARMin III devices have been developed for a multicenter clinical trial. The next section describes the mechanics of the ARMin III robot in more detail.

9.2.2 Mechanical Setup of the ARMin III Robot

The ARMin III robot (Fig. 9.4) has an exoskeleton structure with six electric motors allowing it to move the human arm in all possible directions. Three motors actuate the shoulder joint for shoulder flexion/extension, horizontal abduction/adduction, and internal/external rotation. The elbow joint has two motors that actuate elbow flexion/extension and forearm pronation/supination. The last motor actuates wrist flexion/extension [24]. An optional module to support hand opening and closing can be attached to the ARMin III robot.

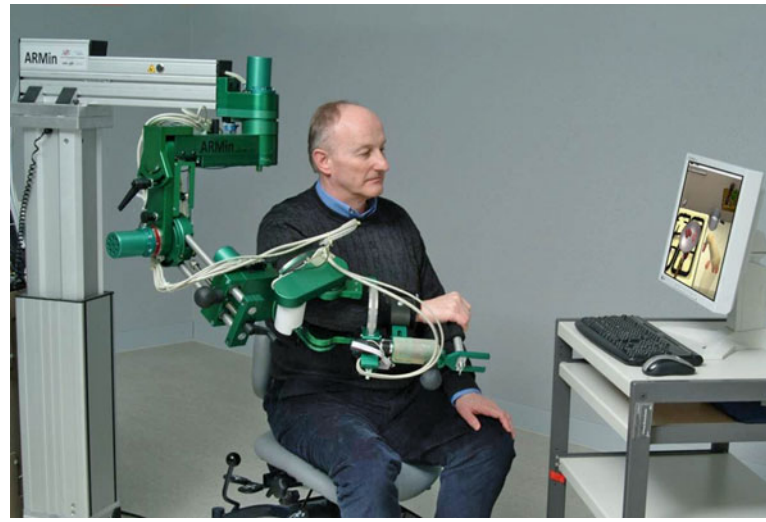

Fig. 9.4 ARMin III setup

All motors are equipped with two position sensors for redundant measurements. The motor and gears are carefully selected so that the friction is small and the backdrivability is good, an important requirement for sensorless force-control [49] and impedance-control strategies.

The patient's arm is affixed to the exoskeleton via two adjustable cuffs, one for the upper arm and one for the lower arm. To accommodate patients of different sizes, the shoulder height can be adjusted via an electric lifting column, and the lengths of the upper and lower arms are adjustable. Laser pointers indicating the center of the glenohumeral joint help the therapist position the patient in the ARMin III device. The ARMin III robot can be configured to accommodate either the left or the right arm. The transition between the two configurations does not require tools and takes less than 15 s.

A spring in the uppermost horizontal robotic link compensates for part of the weight of the exoskeleton. This lessens the load of the electric motor and has the desired effect of balancing the robotic arm when the power is off. Experience has shown that this is crucial for safety and for easy handling of the patient. The robotic shoulder actuation compensates for scapula motion during the arm-elevation movement, resulting in a comfortable and ergonomic shoulder motion [24].

9.2.3 Therapy Modes

The motorized ARMin robots work in three training modes: mobilization, game training, and ADL training. We found it was beneficial to start a typical 1-h training session with a slow and gentle mobilization exercise. Chronic stroke patients in particular seemed to profit from the passive mobilization that reduced spasm and "loosened" the arm and hand. After 10–15 min of passive mobilization, active training followed, including games, reaching exercises, and ADL training scenarios [50, 51].

9.2.3.1 Passive and Active Mobilization

In the mobilization-training mode, the robot moves the patient's arm on a predefined trajectory. The robot is position-controlled, and the feedback loops help the motors compensate for any resistance that the patient produces. This means that, regardless of what the patient is doing, the robot will follow the predefined trajectory. If the patient moves together with the robot in the desired direction (active mobilization), the motors have less work than if the patient remains passive (passive mobilization). However, in both cases, the resulting movement will look the same. Since it is often desirable for the patient to actively contribute to the movement, the motor torque can be measured and used as performance

measure to monitor how actively the patient contributes to the movement. In this case, the audio-visual display is used as feedback modality to let the patient and therapist know how actively the patient is contributing to the movement [45]. Note that, from a technical point of view, this position-controlled training is based on industry-standard position control and is straightforward to implement.

The mobilization requires predefined trajectories that fit the patient's needs in terms of velocity and range of motion. The therapist can either input the data via a computer graphical user interface (GUI) or – more conveniently – use a teach-and-repeat procedure that enables the robot to directly learn a desired trajectory from the therapist. To do this, the therapist moves the robotic arm together with the human arm in the desired way, and the robot records and stores the position data that enable the robot to repeat the movement as shown by the therapist.

9.2.3.2 Game Therapy

Computer games are a good way to motivate the patient to participate actively in the training and contribute as much as possible to a particular movement task. For example, in the ball game, a virtual ball is presented on a computer monitor. It rolls down on an inclined table (Fig. 9.5). The patient can catch the ball with a virtual handle that replicates the movement of the human hand. Thus, the patient "catches" the virtual ball by moving his hand to the appropriate position. An assist-as-much-as-needed control paradigm has been implemented to support the patient in this task: If the patient can catch the ball by himself, the robot does not deliver any support. If the patient cannot catch the ball, the robot supports the patient with an adjustable force that pushes or pulls the hand to the ball position and helps the patient to initiate and execute the appropriate movement.

Whenever the robotic device supports the patient, the color of the handle changes from green to red, and an unpleasant sound is produced to alert the patient and therapist that the robot has supported the movement. The goal for the patient is to perform the task with as little support as possible. The therapist selects the supporting force, typically scaled so that the patient can successfully catch 80% of the balls. Several options enable the therapist to select the therapy mode that best fits the patient's need. For instance, the incline angle of the virtual table can be modified, resulting in faster or slower rolling. The size of the handle and the ball can be changed, and the behavior of the ball (multiple reflections with the wall and the handle) can be changed to challenge the patient further. For some advanced patients, disturbing forces and force fields can be introduced by the robot to make the task harder and to challenge the patient even more. Also, the number and kind of joints, as well as range of motion of the involved joints, can be adjusted to the patient's need.

A prerequisite for this assist-as-needed control strategy is that the intended movement of the patient (i.e., where the patient wants to move his hand) is known. For the ball game, this is the position where the ball falls.

A similar supporting strategy has been implemented for a ping-pong game (Fig. 9.5). Here, the patient holds a virtual ping-pong racket and plays a ping-pong match against a virtual opponent. At the highest level of difficulty, the patient must control the position, orientation, and impulse of the virtual racket to hit the incoming ball so that it lands on the computer-opponent's side of the table. At easier levels, the robot takes care of the orientation and velocity of the racket, and the patient need only move the racket to a position where it will hit the incoming ball.

If required, the robot can also support the patient's arm and provide a force that pulls the hand to the desired spot. To increase the patient's motivation and engagement, a multiplayer application – where the patient plays virtual ping-pong against another patient instead of a virtual opponent – has been implemented and tested. This application allowed remote patients from different hospitals to meet virtually for a virtual ping-pong game.

Another therapeutic computer game is the labyrinth game, where the patient navigates his hand through a virtual labyrinth. A red dot on the screen indicates the actual position of the human hand. The patient must move the red dot through

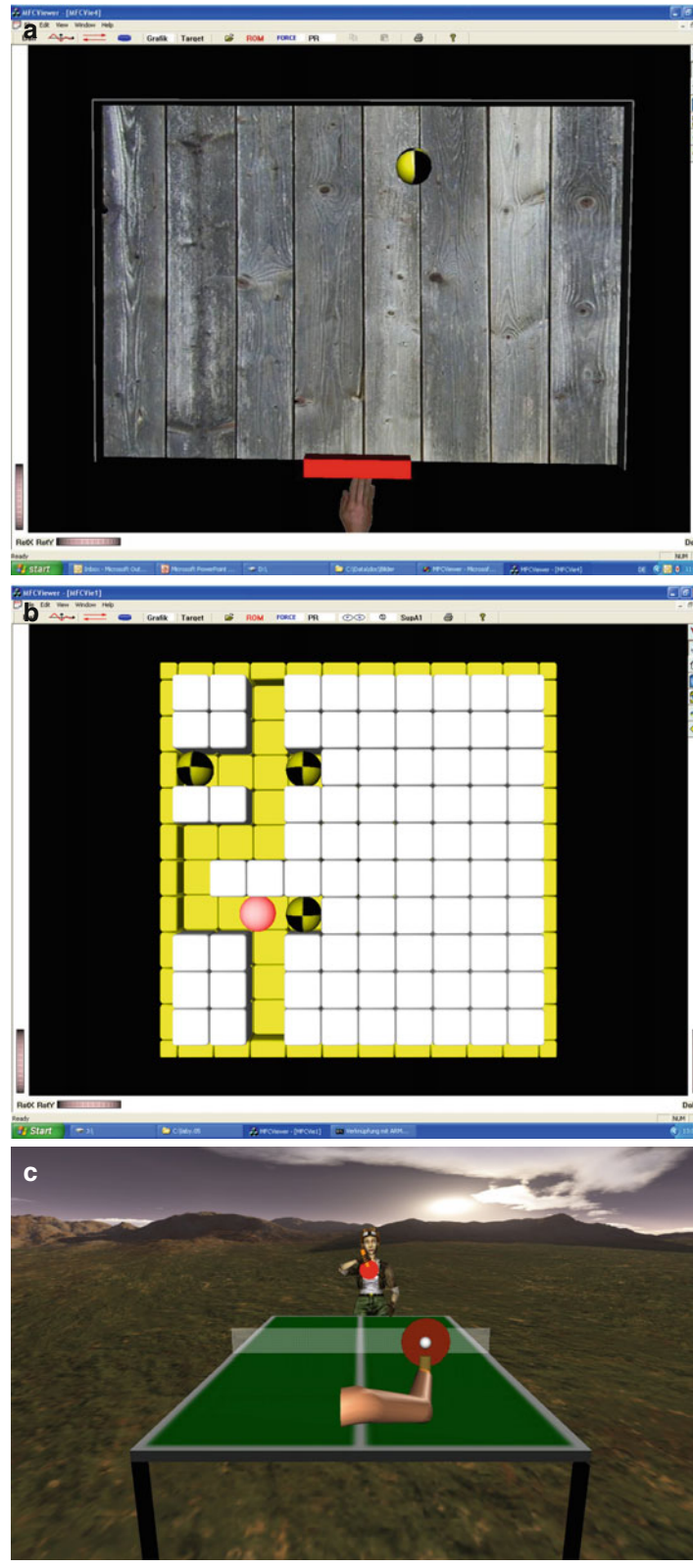

Fig. 9.5 Virtual reality scenarios for arm training. Ball game (**a**), labyrinth (**b**), and ping-pong game (**c**)

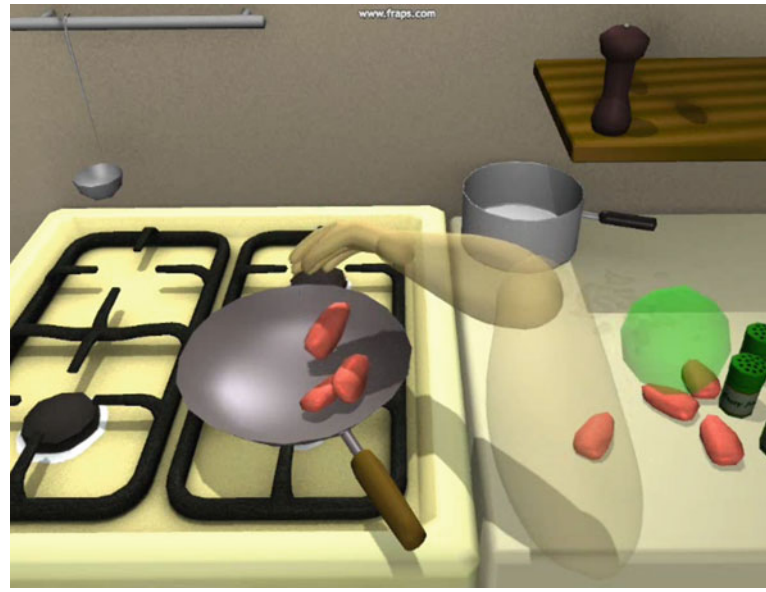

Fig. 9.6 Kitchen scenario

the labyrinth. Virtual walls block the red dot and robot motors produce resistance that prevents the hand from passing through the walls. Force-feedback technology delivers a realistic impression of the virtual wall to the patient.

We found the labyrinth game particularly useful for patient therapy since the patient can use the walls for guidance. By following the walls, his movements remain free in three movement directions and are restricted only in the direction of the wall. This seemed to help patients move their hands on straight lines [51]. If required, the patient can be supported by the robot in completing the labyrinth task. In these instances, the labyrinth task is selected in the way that the patient must elevate his arm in the course of the exercise. This means that the starting point is at the bottom of the labyrinth and the goal is on top of the labyrinth. The therapist can choose from two supporting strategies. One compensates for the weight of the human arm, thus supports the patient in lifting the arm. In case of 100% weight support, the patient's arm somewhat floats, and it is very easy for the patient to lift his arm. In the second supporting scheme, the robot allows upward arm movements but resists downward movements. With this strategy, the patient must lift his arm by himself, but whenever he gets tired, he can rest, and the arm will stay at the current position without any effort. Both strategies can also be combined [52]. To increase patient motivation, scoring is used based on the time, intensity, number, and time of collisions with the wall as well as the number of objects (positioned along the course of the labyrinth) that are collected by the patient.

9.2.3.3 Training of Activities of Daily Living

The purpose of ADL training is to support the patient in relearning ADL tasks, make the training a better simulation of real-life tasks, and further motivate the patient. An ADL task is presented on the computer screen, and the patient tries to complete the task. Like the game therapy, the robot supports the patient as much as needed and only interferes if necessary. Current research focuses on the implementation and evaluation of appropriate ADL tasks for robotic therapy. To date, implemented ADL tasks and used within ARMin therapy include:

- Setting a table
- Cooking potatoes
- Filling a cup
- Cleaning a table
- Washing hands
- Playing the piano
- Manipulating an automatic ticketing machine

For the kitchen scenario (Fig. 9.6), a virtual arm is presented on the computer screen. The

arm reflects the movement of the patient's arm, including shoulder, elbow, wrist, and hand opening and closing movements. A cooking stove, a kitchen table, and a shelf are fixed elements of the scenario. Cooking ingredients include several potatoes, black pepper, salt, and oregano. Available cooking tools include a pan and a dipper. Spoken instructions guide the patient through the cooking process. For instance, the patient must position the pan on the stove, turn on the heat, wait until the pan is hot, grasp the potatoes with his hand and put them into the pan, wait until he hears the sound of roasting, add pepper and salt, and stir the pan.

For this training scenario, the robot supports the patient only as much as needed, the patient has enough freedom to select his own movement trajectory, and the patient always sees feedback on how much he is currently supported by the robotic device. This is technically challenging because the cooking scenario involves several different movements [53, 54]. One possible solution that has been implemented with the ARMin system is to use virtual tunnels spanning from the start point to the goal point [55].

For instance, with the subtask of positioning potatoes in the pan, an invisible virtual tunnel starts at the initial location of the potatoes and ends above the pan. The robot lets the patient move freely within this tunnel. But once the patient hits the walls of the tunnels, the robot resists movement (similar to the labyrinth). Thus, the patient must follow the predefined path and not deviate from it. The diameter of the tunnel defines the amount of freedom the patient has. Furthermore, the patient is also free to select the timing and velocity of the movement. In addition, if required, the robot can also compensate for part of the arm weight and make the movement easier. Similar support strategies are implemented for the other ADL tasks [53].

9.2.4 Measurement Functionality of the ARMin Robot

The ability to objectively assess patient performance is one of the key benefits of robot-supported arm rehabilitation and allows the therapist to quantify therapy effects and patient progress. With the ARMin robot, the following parameters can be measured:

- Active range of motion
- Passive range of motion
- Muscle strength
- Abnormal joint synergies
- Spatial precision of hand positioning

The active and passive range of motion (ROM) are measured for each joint individually. When measuring, for example, the ROM of the elbow joint, all other joints are locked in a predefined position. The joint under investigation is controlled so that the patient can move it without resistance from the robot. The motor is only used to compensate for friction and gravity. The patient is instructed to extend the elbow as much as possible, and the robot measures the position of the elbow and stores the maximum values. When the passive range of motion is determined, the patient remains passive, and the joint is moved by the therapist while the robot records the maximum values of the joint position.

Muscle strength is measured with all joints locked in a predefined position. The motors are position-controlled with a fixed-reference position. Each joint is tested individually. For example, if the muscle strength of the abduction movement is tested, the patient is asked to abduct his arm as much as possible. Since the robot is position-controlled, and – in almost all cases – stronger than the human, the arm will not move. But the electric motor will need more current to work against the abduction torque. By measuring the motor current, the abduction torque can be determined using a model of the ARMin robot. The model describes the effects of gravity, friction, and the current-torque relationship in the electric motor.

Abnormal synergies result from abnormal muscle coactivation and loss of interjoint coordination. This means that, if a patient tries to abduct his arm, this goes together with an elbow flexion, forearm supination, and wrist and finger flexion [56]. To quantify abnormal synergies, all joints are locked in a predefined position. The patient abducts his arm as much as possible, and during the abduction torque, the joint torques produced by the patient in the shoulder, elbow, lower arm, and wrist are measured and recorded by the robotic device.

Currently under development is a procedure to assess the spasticity of the affected arm. Here, the robot moves the human limb at different velocities and measures the required force. This technique has been implemented and evaluated for the lower limb within the Lokomat gait training robot [57].

9.2.5 Evaluation of the ARMin Technology

Three different versions of the ARMin device (I–III) were used to evaluate the ARMin technology. Evaluation of the ARMin technology was carried out with different versions of the ARMin.

9.2.5.1 Technical Tests with Healthy Subjects

Before the robotic device can be used with test subjects, it must be tested without a person in it. The appropriate test procedure verifies device safety and tests all situations defined as critical in the risk-management document. After testing, the technical specifications of the robot were validated by measurement. Table 9.1 shows the measured technical data for the ARMin III robot [24].

The next step was to evaluate the robot with healthy subjects. After appropriate approval by an independent ethics committee (internal review board), a thorough technical evaluation was performed on healthy subjects before the robot was used with patients. After providing written informed consent, the test subjects were exposed to the robotic device. The purposes of this evaluation included:

- Testing the handling of the robotic device. This includes positioning the test subject, adapting the robotic device for different body sizes, changing from left-arm use to right-arm use, and comfort evaluation.
- Functionally testing the software. The questions were whether the test subject understood the instructions, whether he could successfully perform the exercises, and whether he liked the exercises. Special attention was also given to unwanted side effects, i.e., motion sickness and others.

Questionnaires validated the comfort and subjective feelings of the test subjects. One important side effect of this technical testing was that the therapist learned how to manipulate and use the robotic device before being exposed to patients.

Table 9.1 Measured technical data for the ARMin III robot [24]

Maximal endpoint load[a,b]	4.6 kg
Weight (excl. controller, hardware, frame)[b]	18.755 kg
Repeatability (endpoint)[b]	±0.5 mm
Stiffness (endpoint)[a,c]	0.364 mm/M
Force (endpoints)[a,b]	$F_{max} = (451\ N, 804\ N, 706\ N)^T$ with $G = (-g,0,0)^T$
Bandwidth for small endpoint movements (±1.5 cm)[d]	1.28 Hz

[a]Worst-case exoskeleton position
[b]Measured without subject (exoskeleton only)
[c]Stiffness measured at the endpoint by applying 20 N, while the motors are position-controlled
[d]Measured with healthy subject

9.2.5.2 Technical Tests with Stroke Patients

After the tests with healthy subjects concluded, technical tests with stroke patients were performed. After written informed consent was obtained, chronic stroke patients tested the device in one to five therapy sessions. The purpose of these tests was not to measure possible improvements in the patient's health status but to evaluate the technical ergonomic functionality of the ARMin robot. Specific goals included:

- Testing the handling of the ARMin device with stroke patients. Assessing the subjective feelings regarding comfort and ergonomics.
- Evaluating all training modes, including passive and active mobilization, game-supported therapy, and ADL training.
- Testing the level of difficulty of the tasks and the level of assistance that the robot provides to support the patients.
- Assessing patient motivation.

More than 20 stroke subjects participated in these preliminary tests [31].

9.2.5.3 Clinical Pilot Studies with Stroke Patients

A pilot study with three chronic stroke subjects (at least 14 months post-stroke) was performed with the ARMin I robot to investigate whether

arm training with the ARMin I improves motor function of the paretic upper extremity [51]. The study had an A–B design with 2 weeks of multiple baseline measurements (A) and 8 weeks of training (B) with repetitive measurement and follow-up measurement 8 weeks after training. The training included shoulder and elbow movements induced by ARMin I. Two subjects had three 1-h sessions per week, and one subject received five 1-h sessions per week. The main outcome measurement was the upper-limb portion of the Fugl-Meyer Assessment (FMA). It showed moderate, but significant, improvements in all three subjects ($p<0.05$). Most improvements were maintained 8 weeks after discharge. However, patients stated that the daily use of their paretic arm in the real world did not change. This finding was supported by constant ARAT and Barthel Index scores. This could be explained by the fact that, due to limitations of the ARMin I device, primarily non-ADL-related proximal joint movements were trained.

Therefore, another study was performed to investigate effects of intensive arm training on motor performance using the ARMin II robot, where distal joints and ADL tasks were also incorporated into the training [50]. The study was conducted with four chronic stroke subjects (at least 12 months post-stroke). The subjects received robot-assisted therapy over a period of 8 weeks, 3–4 days per week, 1 h per day. Two patients had four 1-h training sessions per week, and the other two patients had three 1-h training sessions per week.

The primary outcome measurement was the upper extremity portion of the FMA. The secondary outcome measures were the Wolf Motor Function Test (WMFT), maximum voluntary joint torques, and additional scores to assess transfer effects. Three out of four patients showed significant improvements ($p<0.05$) in the primary outcome. Improvements in FMA scores aligned with the torque measurements.

Most improvements were maintained, some even further increased, between discharge and a 6-month follow-up. The data clearly indicate that intensive arm therapy with the robot ARMin II can significantly improve motor function of the paretic arm in some stroke patients. Even those who are in a chronic state achieve sustainable improvements. Care must be taken in analyzing the results of this pilot study. Participants were selected outpatients, there was no control group, and there were only four participants. Thus, one cannot generalize these results. However, the result justified the start of a subsequent controlled, randomized, multicenter clinical trial.

9.3 Current Developments and Ongoing Testing

9.3.1 Randomized Clinical Trial

The limitations of the aforementioned studies indicate that a controlled, randomized clinical trial with a blinded assessment of functional outcome with a sufficient number of patients is required to investigate the effectiveness of the ARMin robotic arm treatment in a defined population of chronic stroke patients. A key aspect would be to investigate the effects of ADL training tasks based on reaching and grasping movements. ARMin III provides the required functions: large movement ranges, 3D movements, actuation of proximal and distal joints, patient-responsive control, audiovisual ADL tasks, and more.

Consequently, a prospective, controlled, randomized study was started in 2009. Its goal is to investigate whether task-oriented robot-aided therapy is more effective than conventional therapy in promoting functional recovery of the paralyzed arm. Robotic therapy is being performed with four ARMin III systems at four different hospitals. Within 2 years, 80 chronic stroke patients (more than 6 months post-stroke) will be randomly assigned to either an experimental or control group. The experimental group will perform task-related intensive therapy with ARMin III. Patients in the control group will receive standard motor-relearning therapy. Both groups will be trained for 8 weeks, three times per week, with 1 h for each training session. Outcome measures will be obtained prior to, during, and after the training phase by a blinded therapist. The primary

outcome measure will be the FMA. Further outcome measures will be used to evaluate task-oriented function and its use in the real word. Using the measurement functionality of ARMin, further information will be obtained, including data on abnormal joint synergies, active range of motion, muscle strength, and precision of hand positioning.

9.3.2 Technical Development and Ongoing Testing

Current work includes the development and evaluation of new assessment tools for spasticity measurement [57] and for quantification of abnormal joint synergies [56]. This work is important because the objective and sensitive quantification of therapy progress is crucial for proper clinical evaluations of therapeutic effects.

Another important line of work is to develop and evaluate new training scenarios. A training scenario has an underlying control strategy and a visible audiovisual display (virtual reality). With recent technical innovations, tools are available that allow implementation of sophisticated and realistic graphical scenarios. It remains an open question how an optimal virtual reality (VR) for stroke patients should look. Specific questions to answer are:

- What is the optimal media to present VR to patients (monitor, projection screens, etc.)?
- Is it better to use realistic or simplified graphical scenarios?
- Can 3D technology using stereoscopic vision improve the perception of objects in the 3D space?

The answers to these questions also depend on the patient population. Particularly in stroke patients with hemispheric neglect, the perception of complex graphical scenarios can be difficult and needs further investigation.

The underlying control strategy is a very interesting research question, and a lot of work has been dedicated to develop new patient-responsive control strategies [54, 58, 59]. Assisting a stroke patient in naturalistic ADL tasks (drinking, cooking, eating, dressing, and others) is quite a complex task and requires extensive technical development and clinical testing.

The ARMin III robot also serves as a model for the prototype of the commercial version of the ARMin device, which is being developed by Hocoma AG (Volketswil, Switzerland). The commercial version of the ARMin robot will be named Armeo Power, and it will be further optimized with respect to reliability, mechatronic robustness, user friendliness, ergonomic function, and design, as well as optimized manufacturing processes and costs. The Armeo therapy concept suggested by Hocoma consists of three Armeo products (Fig. 9.7) that are all driven from the same software platform. Each product is optimized for a specific phase of the rehabilitation process. Shortly after injury, a patient with no or very little voluntary activation of arm muscles trains with the motorized robotic device Armeo Power (former ARMin III). Once his motor function improves and some active movements are possible, the patient continues arm training with the nonmotorized, weight-supported exoskeleton Armeo Spring (former T-Wrex) [26]. After further improvements, the patient might continue training with the Armeo Boom, which consists of an overhead sling suspension system. This training seems suitable for patients who can actively move the arm but suffer from reduced workspace and poor motor control [60].

A successful commercialization would be beneficial for obtaining more clinical data of specific rehabilitation robots since a large number of rehabilitation facilities would use the same device for clinical practice and for research.

9.4 Perspectives and Conclusions

Upper-limb rehabilitation is one of the fastest growing areas in modern neurorehabilitation. Quality of life can be significantly improved when applying efficient arm therapy. The results of the pilot studies that have been presented within this chapter suggest that the new technology can be an important means to improve arm therapy. Thus, for the future, one might envision a combined training paradigm including both

Fig. 9.7 The Armeo Product line, with the commercial version of the ARMin device Armeo®Power (**a**), Armeo®Spring (**b**), and Armeo®Boom (**c**) (Copyright Hocoma AG, Switzerland, www.hocoma.com)

manual and additional robot-supported therapy. The technology for upper-limb rehabilitation with three-dimensional multi-degree-of-freedom arm robots is quite mature and will be commercially available very soon. However, the clinical data of the therapeutic effect currently are incomplete, and future work should focus on the evaluation of the clinical benefits. Further randomized clinical trials similar to the aforementioned ARMin study should be undertaken. Studies with focus on both the overall benefit of the combined technology (VR, robot, assist-as-needed control strategies, etc.) or studies comparing the influence of single elements (i.e., VR vs. robotics) are needed. These studies will require large numbers of participants, a multicenter setting, and several robotic devices of the same type. It is crucial that these robots will be reliable, easy to use, and supported and maintained by a professional organization. Therefore, it is expected that the numbers of clinical data and clinical studies will increase once the technology becomes commercially available.

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References

1. Brainin M, Bornstein N, Boysen G, Demarin V. Acute neurological stroke care in Europe: results of the European Stroke Care Inventory. Eur J Neurol. 2000;7:5–10.
2. Thorvaldsen P, Asplund K, Kuulasmaa K, Rajakangas AM, Schroll M. Stroke incidence, case fatality, and mortality in the WHO MONICA project. World Health Organization Monitoring Trends and Determinants in Cardiovascular Disease. Stroke. 1995;26(3):361–7.
3. Rosamond W, Flegal K, Friday G, et al. Heart disease and stroke statistics update. a report from the American Heart Association Statistics Committee and Stroke Statistics Subcommittee. Circulation. 2007;115:69–171.
4. Maeurer HC, Diener HC. Der Schlaganfall. Stuttgart: Georg Thieme Verlag; 1996.
5. Rossini PM, Calautti C, Pauri F, Baron JC. Post-stroke plastic reorganisation in the adult brain. Lancet Neurol. 2003;2:493–502.
6. Nakayama H, Jrgensen HS, Raaschou HO, Olsen TS. Recovery of upper extremity function in stroke patients: the Copenhagen Stroke Study. Arch Phys Med Rehabil. 1994;75:394–8.
7. Barreca S, Wolf SL, Fasoli S, Bohannon R. Treatment interventions for the paretic upper limb of stroke survivors: a critical review. Neurorehabil Neural Repair. 2003;17(4):220–6.
8. Platz T. Evidence-based arm rehabilitation – a systematic review of the literature. Nervenarzt. 2003;74(10):841–9.
9. Dobkin BH. Strategies for stroke rehabilitation. Lancet Neurol. 2004;3(9):528–36.
10. Ottenbacher KJ, Jannell S. The results of clinical trials in stroke rehabilitation research. Arch Neurol. 1993;50:37–44.
11. Kwakkel G, Wagenaar RC, Koelman TW, Lankhorst GJ, Koetsier JC. Effects of intensity of rehabilitation after stroke. A research synthesis. Stroke. 1997;28(8):1550–6.
12. Nelles G. Cortical reorganization- effects of intensive therapy. Arch Phys Med Rehabil. 2004;22:239–44.
13. Sunderland A, Tinson DJ, Bradley EL, Fletcher D, Langton Hewer R, Wade DT. Enhanced physical therapy improves recovery of arm function after stroke. A randomised controlled trial. J Neurol Neurosurg Psychiatry. 1992;55(7):530–5.
14. Kwakkel G, Kollen BJ, Wagenaar RC. Long term effects of intensity of upper and lower limb training after stroke: a randomised trial. J Neurol Neurosurg Psychiatry. 2002;72:473–9.
15. Butefisch C, Hummelsheim H, Denzler P, Mauritz KH. Repetitive training of isolated movements improves the outcome of motor rehabilitation of the centrally paretic hand. J Neurol Sci. 1995;130:59–68.
16. Prange GB, Jannink MJA, Groothuis-Oudshoorn CGM, Hermens HJ, MJ Ijzerman. Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke. J Rehabil Res Dev. 2006;43:171–84.
17. Riener R, Nef T, Colombo G. Robot-aided neurorehabilitation for the upper extremities. Med Biol Eng Comput. 2005;43:2–10.
18. Kwakkel G, Kollen BJ, Krebs HI. Effects of robot-assisted therapy on upper limb recovery after stroke: a systematic review. Neurorehabil Neural Repair. 2008;22(2):111–21.
19. Krebs HI, Ferraro M, Buerger SP, et al. Rehabilitation robotics: pilot trial of a spatial extension for MIT-Manus. J Neuroeng Rehabil. 2004;1:5–9.
20. Lum PS, Burgar CG, Shor PC, Majmundar M, Van der Loos M. Robot-assisted movement training compared with conventional therapy techniques for the rehabilitation of upper-limb motor function after stroke. Arch Phys Med Rehabil. 2002;83(7):952–9.
21. Hesse S, Werner C, Pohl M, Mehrholz J, Puzich U, Krebs HI. Mechanical arm trainer for the treatment of the severely affected arm after a stroke: a single-blinded

randomized trial in two centers. Am J Phys Med Rehabil. 2008;87(10):779–88.
22. Coote S, Murphy B, Harwin W, Stokes E. The effect of the GENTLE/s robot-mediated therapy system on arm function after stroke. Clin Rehabil. 2008;22(5): 395–405.
23. Dewald J, Ellis MD, Holubar BG, Sukal T, Acosta AM. The robot application in the rehabilitation of stroke patients. Neurol Rehabil. 2004;4:S7.
24. Nef T, Guidali M, Riener R. ARMin III – arm therapy exoskeleton with an ergonomic shoulder actuation. Appl Bionics Biomech. 2009;6(2):127–42.
25. Stienen AHA, Hekman EEG, Van der Helm FCT, et al. Dampace: dynamic force-coordination trainer for the upper extremities. Proc IEEE. 2007;10: 13–5.
26. Sanchez RJ, Liu J, Rao S, et al. Automating arm movement training following severe stroke: functional exercise with quantitative feedback in a gravity-reduced environment. IEEE Trans Neural Syst Rehabil Eng. 2006;14:378–89.
27. Carignan C, Liszka M. Design of an arm exoskeleton with scapula motion for shoulder rehabilitation. Paper presented at: Proceedings of the 12th international conference on advanced robotics, Seattle; 18–20 Jul 2005.
28. Frisoli A, Borelli L, Montagner A, et al. Arm rehabilitation with a robotic exoskeleleton in virtual reality. In: 2007 IEEE 10th international conference on rehabilitation robotics, Vols 1 and 2, Noordwijk; 2007. p. 631–42.
29. Rosen J, Perry JC, Manning N, Burns S, Hannaford B. The human arm kinematics and dynamics during daily activities – toward a 7 DOF upper limb powered exoskeleton. In: 2005 12th international conference on advanced robotics, Seattle; 2005, p. 532–9.
30. Zhang LQ, Park FS, Ren YP. Developing an intelligent robotic arm for stroke rehabilitation. In: 2007 IEEE 10th international conference on rehabilitation robotics, Vols 1 and 2, Noordwijk; 2007, p. 984–93.
31. Nef T, Mihelj M, Riener R. ARMin: a robot for patient- cooperative arm therapy. Med Biol Eng Comput. 2007;45:887–900.
32. Bayona NA, Bitensky J, Salter K, Teasell R. The role of task-specific training in rehabilitation therapies. Top Stroke Rehabil. 2005;12:58–65.
33. Wolf SL, Lecraw DE, Barton LA, Jann BB. Forced use of hemiplegic upper extremity to reverse the effect of learned nonuse among chronic stroke and head-injured patients. Exp Neurol. 1989;104:125–32.
34. Taub E, Uswatte G, Pidikiti R. Constraint-induced movement therapy: a new family of techniques with broad application to physical rehabilitation – a clinical review. J Rehabil Res Dev. 1999;36:237–51.
35. Miltner WHR, Bauder H, Sommer M, Dettmers C, Taub E. Effects of constraint-induced movement therapy on patients with chronic motor deficits after stroke. A replication. Stroke. 1999;30:586–92.
36. Dromerick AW, Edwards DF, Hahn M. Does the application of constraint-induced movement therapy during acute rehabilitation reduce arm impairment after ischemic stroke? Stroke. 2000;31:2984–8.
37. Lambercy O, Dovat L, Gassert R, Burdet E, Teo CL, Milner T. A haptic knob for rehabilitation of hand function. IEEE Trans Neural Syst Rehabil Eng. 2007;15(3):356–66.
38. Hesse S, Schulte-Tigges G, Konrad M, Bardeleben A, Werner C. Robot-assisted arm trainer for the passive and active practice of bilateral forearm and wrist movements in hemiparetic subjects. Arch Phys Med Rehabil. 2003;84:915–20.
39. Krebs HI, Volpe BT, Williams D, et al. Robot-aided neurorehabilitation: a robot for wrist rehabilitation. IEEE Trans Neural Syst Rehabil Eng. 2007;15(3):327–35.
40. Hesse S, Werner C, Pohl M, Rueckriem S, Mehrholz J, Lingnau ML. Computerized arm training improves the motor control of the severely affected arm after stroke: a single-blinded randomized trial in two centers. Stroke. 2005;36(9):1960–6.
41. Muellbacher W, Richards C, Ziemann U, et al. Improving hand function in chronic stroke. Arch Neurol. 2002;59(8):1278–82.
42. Krebs HI, Hogan N, Aisen ML, Volpe BT. Robot-aided neurorehabilitation. IEEE Trans Rehabil Eng. 1998;6:75–87.
43. Ellis MD, Sukal-Moulton TM, Dewald JP. Impairment-based 3-D robotic intervention improves upper extremity work area in chronic stroke: targeting abnormal joint torque coupling with progressive shoulder abduction loading. IEEE Trans Robot. 2009;25(3):549–55.
44. Bolliger M, Banz R, Dietz V, Lunenburger L. Standardized voluntary force measurement in a lower extremity rehabilitation robot. J Neuroeng Rehabil. 2008;5:23.
45. Lunenburger L, Colombo G, Riener R. Biofeedback for robotic gait rehabilitation. J Neuroeng Rehabil. 2007;4:1.
46. Housman SJ, Scott KM, Reinkensmeyer DJ. A randomized controlled trial of gravity-supported, computer-enhanced arm exercise for individuals with severe hemiparesis. Neurorehabil Neural Repair. 2009;23(5):505–14.
47. Nef T, Mihelj M, Colombo G, Riener R. ARMin robot for rehabilitation of the upper extremities. In: IEEE international conference on robotics and automation, Orlando; 2006, p. 3152–7.
48. Mihelj M, Nef T, Riener R. ARMin II – 7 DoF rehabilitation robot: mechanics and kinematics. In: Proceedings of the 2007 IEEE international conference on robotics and automation, Vols 1–10, Rome; 2007, p. 4120–5.
49. Nef T, Lum P. Improving backdrivability in geared rehabilitation robots. Med Biol Eng Comput. 2009;47(4):441–7.

50. Staubli P, Nef T, Klamroth-Marganska V, Riener R. Effects of intensive arm training with the rehabilitation robot ARMin II in chronic stroke patients: four single-cases. J Neuroeng Rehabil. 2009;6:46.
51. Nef T, Quinter G, Muller R, Riener R. Effects of arm training with the robotic device ARMin I in chronic stroke: three single cases. Neurodegener Dis. 2009; 6(5–6):240–51.
52. Nef T, Mihelj M, Kiefer G, Perndl C, Mueller R, Riener R. ARMin – exoskeleton for arm therapy in stroke patients. In: 2007 IEEE 10th international conference on rehabilitation robotics, Vols 1 and 2, Noordwijk; 2007, p. 68–74.
53. Guidali M, Duschau-Wicke A, Broggi S, Klamroth-Marganska V, Nef T, Riener R. Med Biol Eng Comput. 2011 Oct;49(10):1213-23. Epub 2011 Jul 28.PMID:21796422.
54. Mihelj M, Nef T, Riener R. A novel paradigm for patient-cooperative control of upper-limb rehabilitation robots. Adv Robot. 2007;21(8):843–67.
55. Duschau-Wicke A, von Zitzewitz J, Caprez A, Lunenburger L, Riener R. Path control: a method for patient-cooperative robot-aided gait rehabilitation. IEEE Trans Neural Syst Rehabil Eng. 2010;18(1): 38–48.
56. Dewald JP, Beer RF. Abnormal joint torque patterns in the paretic upper limb of subjects with hemiparesis. Muscle Nerve. 2001;24:273–83.
57. Schmartz AC, Meyer-Heim AD, Muller R, Bolliger M. Measurement of muscle stiffness using robotic assisted gait orthosis in children with cerebral palsy: a proof of concept. Disabil Rehabil Assist Technol. 2011;6(1):29–37.
58. Riener R, Lunenburger L, Jezernik S, Anderschitz M, Colombo G, Dietz V. Patient-cooperative strategies for robot-aided treadmill training: first experimental results. IEEE Trans Neural Syst Rehabil Eng. 2005;13(3):380–94.
59. Marchal-Crespo L, Reinkensmeyer DJ. Review of control strategies for robotic movement training after neurologic injury. J Neuroeng Rehabil. 2009;6:20.
60. Prange GB, Jannink MJ, Stienen AH, van der Kooij H, Ijzerman MJ, Hermens HJ. Influence of gravity compensation on muscle activation patterns during different temporal phases of arm movements of stroke patients. Neurorehabil Neural Repair. 2009;23(5):478–85.