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REVIEW ARTICLE

A review of technological and clinical aspects of robot-aided rehabilitation of upper-extremity after stroke

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Abstract

Cerebrovascular accident (CVA) or stroke is one of the leading causes of disability and loss of motor function. Millions of people around the world are effected by it each year. Stroke results in disabled arm function. Restoration of arm function is essential to regaining activities of daily living (ADL). Along with traditional rehabilitation methods, robot-aided therapy has emerged in recent years. Robot-aided rehabilitation is more intensive, of longer duration and more repetitive. Using robots, repetitive dull exercises can turn into a more challenging and motivating tasks such as games. Besides, robots can provide a quantitative measure of the rehabilitation progress. This article overviews the terms used in robot-aided upper-limb rehabilitation. It continues by investigating the requirements for rehabilitation robots. Then the most outstanding works in robot-aided upper-limb rehabilitation and their control schemes have been investigated. The clinical outcomes of the built robots are also given that demonstrates the usability of these robots in real-life applications and their acceptance. This article summarizes a review done along with a research on the design, simulation and control of a robot for use in upper-limb rehabilitation after stroke.

➤ Implications for Rehabilitation

- Reviewing common terms in rehabilitation of upper limb using robots
- Reviewing rehabilitation robots built up to date
- Reviewing clinical outcomes of the mentioned rehabilitation robots

Keywords

ADL training, clinical testing of rehabilitation robots, impedance control, physiotherapy, robot-aided rehabilitation, stroke, upper-extremity

History

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Introduction

Cerebrovascular accident (CVA) or stroke is one of the leading reasons of disability and loss of motor function, especially in growing population of old people. It affects more than one million people in European Union each year [1,2]. In the United States more than 0.7 million people are affected by stroke each year [3]. Stroke can be defined as ischemic or hemorrhagic disturbance in the blood supply to brain tissue. In the first type the blood supply to the brain is interrupted by a blood clot and in the latter by internal bleeding. The result is partial destruction of cortical tissue that leads to disturbed neural commands from the sensorimotor areas of the cortex which results in reduced or even absent ability to selectively activate muscles which in turn affects motor task performance, leading to impaired arm and hand motor function. According to the study by Rossini et al. [4], degrees of recovery depend on two factors: (1) location of the lesion and (2) severity of the lesion. According to the study by Nakayama et al. [5], only 18% of stroke survivors regain full motor function after 6 months. Considering the mentioned issues, using different therapy approaches is necessary to regain motor function and improve functional outcomes. According to literature [6–8], sensorimotor arm therapy has positive effects on the rehabilitation progress of stroke patients. Relevant factors for successful training are training intensity [9–11], duration [12,13] and repetition [14]. High-intensity and task-specific upper-limb treatment consists of active and highly repetitive movements, which is considered to be one of the most effective approaches to arm and hand function restoration. In fact, the type of therapy matters less than the exercise intensity. Optimal restoration of arm and hand function is essential to independently perform activities of daily living (ADL). The most common approach in stroke rehabilitation is one-to-one manually-assisted training or physiotherapy. This approach is labor-intensive, time-consuming and expensive. Besides, training sessions are often shorter than required for an optimal therapeutic outcome, the therapy varies from one therapist to another and from one hospital to another and is based on theories and therapist's experience. Furthermore, manually-assisted training lacks repeatability and objective measures of patient performance and progress. Taking all these constraints into consideration, robots can help to improve rehabilitation and become an important tool in stroke rehabilitation. Robot-aided arm therapy is more intensive, of longer duration and more repetitive. Using robots, number and duration

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of training sessions can be increased, while reducing the number of therapists required per patient, which in turn yields to reduced personnel costs. Furthermore, robot-aided therapy provides quantitative measures and supports objective observation and evaluation of the rehabilitation progress. Most robotic devices provide a means for ADL training. The reason for incorporating ADL training in robotic devices is that according to literature [8,15], functional and task-oriented training shows good results in stroke patients. Constrained-induced movement therapy, which is a common approach in stroke rehabilitation, involves intensive and repetitive exercise of the most affected limb coupled with constraint of the opposite limb, proved to result in a positive cortical reorganization in the motor cortex. In fact, forcing the affected limb to perform ADL yields functional gains, increases patient motivation and allows the stroke patient to increase the use of the affected arm in the real-world environment [16–19]. Therapy that focuses on ADL training is also called motor relearning program. Several studies showed that robot-aided therapy indeed improves motor function more than the conventional therapy [20–22]. According to the traditional assumption, most recovery occurs within the first 3–6 months post-stroke with no further improvements later on. But in more recent publications it is stated that the chronic patients, i.e. more than 6 months post-stroke, can also improve upper-limb function. In robot-aided therapy, moderately-affected patients are more responsive to therapy than severely-affected patients. It is better that severely-affected patients go on some conventional therapy before exposing to robot-aided therapy. It is worth noting that in robotic rehabilitation, the aim is not to replace human therapist by the robot, but the aim of robotics and automation technology is to assist, enhance, evaluate and document the rehabilitation movements. Finally, it is worth considering that upper-limb recovery is more difficult than lower-limb recovery due to upper-limb's anatomical complexity and the fact that in the case of stroke, the parts of the brain that are responsible for upper-limb movement are more prone to injury.

Rehabilitation robots

Classification of rehabilitation robots

Rehabilitation robots can be categorized in several ways. They can be categorized based on their mechanical structure, number and type of actuated joints, actuation principle and place of setup. From mechanical structure point of view, rehabilitation robots can be categorized as end-effector-based robots and exoskeleton-type robots. End-effector-based robots (Figure 1a) are connected to patient's hand or forearm at one point. Depending on the degrees of freedom (DOFs) of the robot, human arm can be positioned and oriented in space. Robot's axes generally do not correspond to the human-joint rotation axes. From mechanical point of view, end-effector-based robots are easier to build and use. The robot is body or wall-grounded and feedback forces can be applied only to the human hand. End-effector-based robots cannot influence human arm redundancy and are mostly not redundant themselves. In rehabilitation, this class of robots cannot induce joint trajectories exactly matching the human joints. The advantageous features of these robots are that they can easily adjust to different arm lengths; they are simple, usable and cost-effective. The disadvantageous feature is that in general the arm posture or the individual joint interaction torques, are not fully determined by the robot, because the patient and the robot interact just through one point, i.e. the robot's end-effector. Figure 1 [24] depicts types of rehabilitation robots. A typical example of end-effector-based robots that is also commercialized and used in several rehabilitation centers is MIT-MANUS.

Exoskeleton-type robots can be further categorized into two groups: (1) exoskeletons that are kinematically equivalent to human-limb (Figure 1b) and (2) exoskeletons that are kinematically different with respect to the human-limb (Figure 1c). First group of exoskeletons has exactly the same degrees of redundant mobility as the human arm, excluding shoulder girdle, i.e. seven DOFs. This class of robots is body or wall-grounded and is attached at several locations along the limb. In order to induce exact joint trajectories and to match natural redundancy, the robot's joints must be aligned to coincide with the human joints. This feature is important because in the case of mismatch undesired reaction forces can be created in the human joints. The term dynamic manipulability which is defined as the relationship between joint torque and end-effector acceleration has an important role in this type of exoskeletons. In the case of kinematical mismatch, manipulability ellipsoids of both exoskeleton and human limb will not be the same and this will rise to dynamic interaction forces that will be felt by the patient as resistance to motion. The second group of exoskeletons possesses multiple degrees of redundancy to cope with the interaction, not only with the human arm but also with the human shoulder and shoulder girdle. As human shoulder girdle is a complex joint, it requires advanced mechanical solutions. Compared to exoskeletons of the first group, these exoskeletons feature a greater working range and no exact alignment is required between the exoskeleton and the patient. In the case of mismatch and rising reaction forces, the additional DOFs can be exploited until those

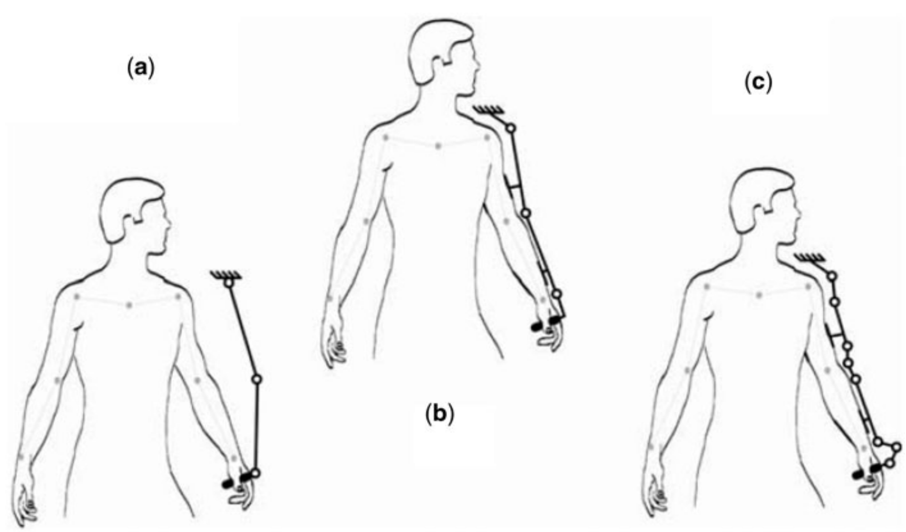

Figure 1. Types of rehabilitation robots: (a) end-effector-based robot, (b) exoskeleton kinematically equivalent to human limb, (c) exoskeleton kinematically not equivalent to human limb [24].

forces are gone. This feature remarkably reduces the setup up time. In general, the disadvantageous feature of exoskeletons is that adaptation to different body sizes is more difficult than end-effector-based robots, because the length of each robot segment must be adjusted to the patient's arm length. Exoskeleton robots also have several advantageous features: the arm posture can be fully determined by this class of robots. Furthermore, the applied torques to each joint of the human arm can be controlled separately. This feature is essential especially 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. This is why therapists use both hands to mobilize a spastic elbow joint. To avoid inducing forces to the shoulder, one hand holds the lower arm and the other hand holds the upper arm. In exoskeletons, similar to manual therapy a cuff is fastened to the lower arm and another cuff is fastened to the upper arm. The majority of exoskeletons are developed as haptic devices for virtual reality (VR) applications. A very good example of exoskeleton-type robots is ARMin robot [23–26].

From number of actuated joints point of view, rehabilitation robots can be classified into several classes. In the first class, the focus is placed on functional training based on ADL including the entire arm and hand, i.e. proximal and distal joints. Example of robotic devices that can provide such training are: GENTLE/s, Dampace, the Armeo Spring and ARMin robot. In the second class, the focus of training is on distal parts of the human arm such as hand [27], the wrist and the lower arm [28,29]. According to Hesse et al. [30], the distal approach results in a more powerful activation of the sensorimotor cortex. The recently suggested competition between proximal and distal arm segments for plastic brain territory after stroke suggests shifting treatment emphasis from the shoulder to the forearm, hand and fingers [31]. The third and last class focuses on training of more proximal parts of human arm including elbow and shoulder [32].

From actuation principle point of view, rehabilitation robots can be classified into passive, active and interactive systems. Active robots are mostly powered by electric, pneumatic or hydraulic actuators. Electric motors have very low power-to-weight ratios. This limits the force output of the robot for physical therapy applications. Pneumatic actuators have high power-to-weight ratio, but the actuator response is too bandwidth-limited for functional rehabilitation. The actuators can either control the interaction force/torque between the patient and the robot or the position of the robot, which allows the robotic device to support the human arm against gravity. Active robots can either support the patient in movement toward a target or can resist the patient in the movement, i.e. making the patient's arm heavier or making the patient feel that he/she is carrying an object with a given mass. Active robots can be used as an evaluation tool to objectively measure voluntary force, range of motion (ROM) and level of spasticity [33,34]. Compared with active robots, passive robots are low cost, low weight, intrinsically safe and easier to use. The disadvantageous feature of passive robots is that they are unable to support the patient other than against gravity. For example, the device cannot support the patient in directed reaching movement nor can it challenge the patient by resisting movement. In some robotic devices, this disadvantageous feature can be overcome by adding brakes to the robot to dissipate energy and challenge the patient's movements [35]. Typical technical components for passive robots are: stiff frames, bearings, pulleys, ropes and counter-weights. Passive robots are suitable for training of mildly impaired stroke patients who do not need as much support as heavily impaired subjects [36]. Interactive robots are characterized not only by actuators but also by sophisticated impedance and other control strategies in order to allow reaction to the patient's efforts. These systems require position and force sensors to measure the user-machine interaction and feed the controllers.

From place of setup point of view, rehabilitation robots can be classified into robots that are mainly used in clinical environments that is being shared by several patients or home-use systems that assist a single patient in ADL.

Training modes in rehabilitation robots

Different training modes can be implemented in rehabilitation robots. Passive movement mode, in which the robotic device moves the patient's arm through a predefined path, is possible in all robotic devices. Active-assisted movement mode, in which the patient initiates the movement and is partially assisted by the robotic device if he/she was not able to perform the task, is also possible in all robotic devices. Active-resisted movement mode, in which the patient initiates the movement and is resisted by robotic device to challenge patient's movement, is implemented in MIT-MANUS, Bi-Manu-Track and MIME. Bimanual training mode, in which the active movements of the unaffected arm are mirrored by simultaneous passive movement of the affected arm by the robotic device, is only implemented in Bi-Manu-Track and MIME [20].

Requirements for a rehabilitation robot

There are several requirements to be considered while designing a rehabilitation robot. These requirements will be stated next. The aim of rehabilitation robots is not to replace the therapist but to make her/his job easier, so the therapist should remain as a person who the patient has confidence in. The therapist is a key person for a successful therapy. The robot should support the therapy defined by the therapist. In no circumstances should the patient be afraid of the robot. These can be put into psychological aspects. The robot should be adaptable to the human limb in terms of segment lengths, ROM and DOFs. High DOF will allow broad variety of movements with many anatomical joint axes involved. These can be put into medical aspects. The robot should be easy to use, flexible to suit different applications. Patients of either gender and different body sizes and weights should be able to use the device. The robot should also share some additional space for equipment accompanied by the patient. These are put into ergonomic aspects. Backdrivability is another important issue to be considered. The weight of the robot should not be felt by the patient and he/she should be able to move the robotic device easily. This can be achieved by using backdrivable hardware. Achieving the dual goals of high-force production capability and backdrivability is an engineering challenge in rehabilitation robots. The robot must be capable of generating sufficient force to move a patient's limb, it must also be easily movable by an elderly or impaired patient [25,37].

Upper-limb kinematics and dynamics

Kinematics of upper limb

Human body is composed of bones linked by joints to form the skeleton. The skeleton is covered by soft tissues like organs and muscles. There are three body planes in which movement of each joint can be defined. They are: (1) sagittal or lateral plane that divides the body into right and left planes, (2) transversal or horizontal plane that divides the body into upper and lower parts, and (3) frontal or coronal plane that divides the body into anterior and posterior parts. Figure 2 (right) [24] depicts human body planes. Movement in the sagittal plane is called flexion and extension. Flexion is a movement that reduces the angle between bones or part of the body, and extension is a movement that

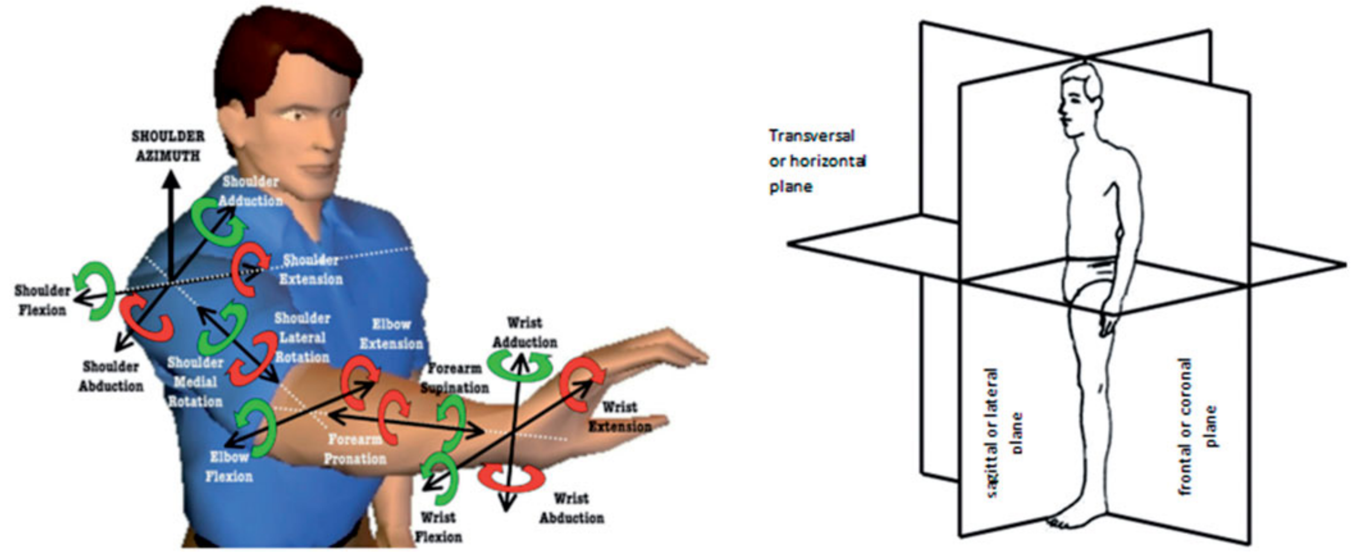

Figure 2. Human arm movements [26] (left), human anatomical planes [24] (right).

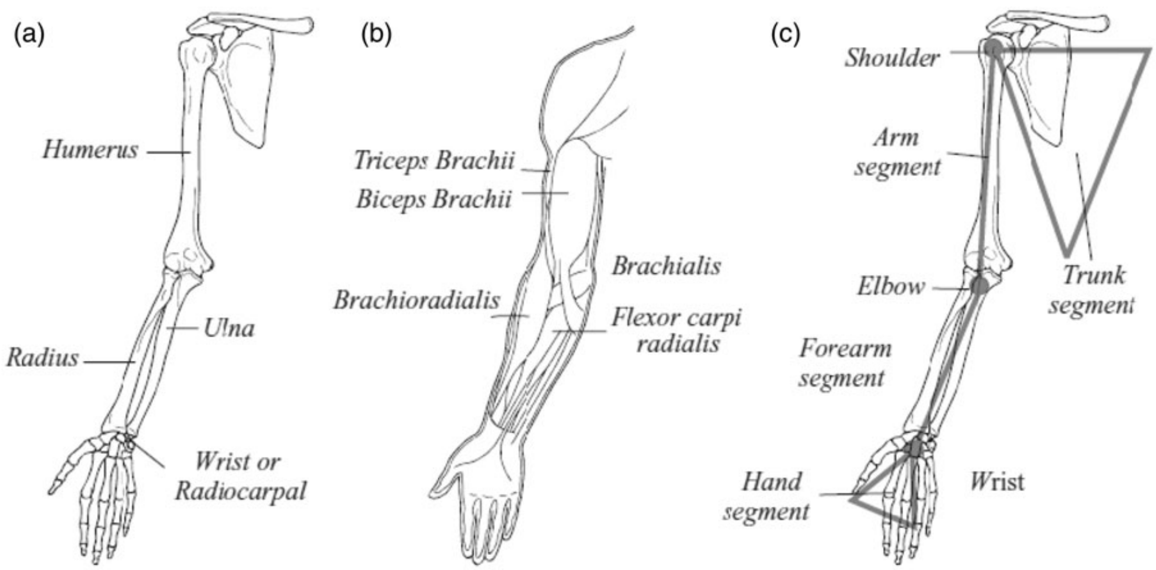

Figure 3. Anatomy of upper limb: (a) bones, (b) muscles, (c) rigid-segment model [24].

increases the angle between the bones of the limb at a joint. Movement in the coronal plane is called abduction and adduction. Abduction is an outward movement of the limb away from the median plane of the body and adduction is a movement that brings a limb closer to the body in the sagittal plane. Another movement is pronation and supination. Supination is rotation of the forearm so that the palm position is anterior, i.e. the palm facing up and pronation is rotation of the forearm that moves the arm from an anterior-facing position to a posterior-facing position, i.e. the palm facing down. Rotation is the movement of a joint around the long axis of the limb in a circular motion. Rotation can be either internal or external. Another movement is circumduction. The circumduction is a circular movement in which flexion, abduction, extension and adduction are combined in a sequence. The most commonly used example is shoulder joint. Figure 2 (left) [26] depicts human arm movements.

The upper limb or the arm is the region from the shoulder to the finger tips. The arm is composed of three segments: the upper arm, the forearm and hand. These three segments are linked by three joints: the shoulder, the elbow and the wrist. Figure 3 [24] depicts the anatomy of the upper limb including bones, muscles and rigid-segment model. Bones that form the upper limb are: clavicle, scapula and humerus in upper arm, radius and ulna in the forearm, carpal bones, metacarpal bones and phalanges in the wrist and hand. The shoulder joint is one of the most complex joints of the human body. The hemispherical head of the humerus (upper arm) forms a ball-and-socket-type synovial joint with the glenoid cavity of the scapula. Human shoulder joint is at least three DOFs and includes three bones: clavicle, scapula and humerus. The three DOFs for shoulder joint are: flexion/extension, abduction/adduction and internal and external rotation. ROM of the shoulder in flexion is between 130 and 180 degrees, and ROM of shoulder in extension is between 30 and 80 degrees. Human shoulder can attain up to 180 degrees of abduction and 50 degrees of adduction. Medial (internal) rotation of the shoulder is between 60 and 90 degrees. The shoulder can attain up to 90 degrees lateral (external) rotation. The elbow joint links the upper arm to the lower arm. It is considered as a hinge joint between the distal end of the humerus and the proximal end of ulna and radius. It is usually assumed one joint with two DOFs. The two DOFs of the elbow joint are: flexion/extension and pronation/supination. Active maximal flexion of elbow is between 140 and 146 degrees

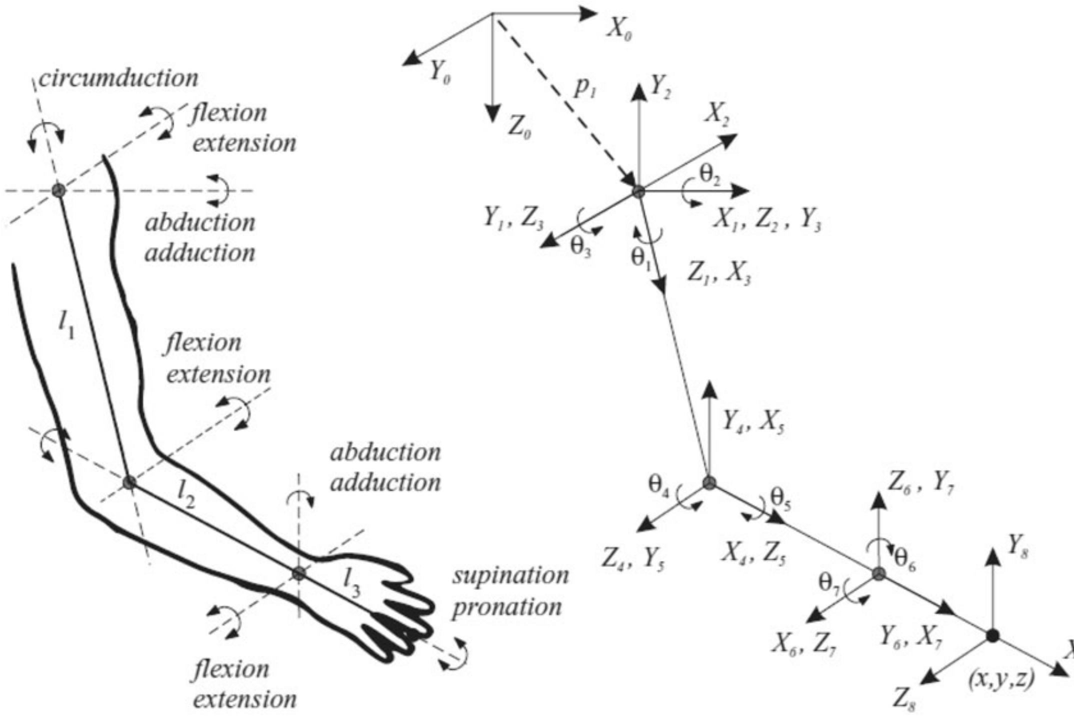

Figure 4. Coordinate assignment for upper limb [24].

Table 1. DH parameters of upper limb [24].

Joint	β_i	α_i	a_i	d_i	θ_i
Base	0	0	a_0	d_0	0
Shoulder	(−90) medial rotation/lateral rotation (+90)	−90	0	0	β_1+90°
Shoulder	(−180) abduction/adduction (+50)	+90	0	0	β_2+90°
Shoulder	(−180) flexion/extension (+50)	0	l_1	0	β_3+90°
Elbow	(−10) extension/flexion (+145)	+90	0	0	β_4+90°
Elbow	(−90) pronation/supination (+90)	+90	0	l_2	β_5+90°
Wrist	(−90) flexion/extension (+70)	+90	0	0	β_6+90°
Wrist	(−15) abduction/adduction (+40)	0	l_3	0	β_7

and its passive flexion is up to 160 degrees. Elbow angle range in ADL is between 30 and 130 degrees. Elbow full extension is 0 degrees. Pronation and supination movements of the elbow are defined from a starting position with the elbow flexed at 90 degrees. The elbow pronation is up to 80 degrees and the elbow supination is up to 85 degrees. The wrist joint is one of the most complex joints in the human body. It is usually modeled as a joint with two DOFs: flexion/extension and abduction/adduction. Wrist active flexion is up to 90 degrees and wrist extension is less than flexion and up to 80 degrees. Wrist adduction is up to 30 or 40 degrees and wrist abduction do not exceed 15 degrees. In humans the ROM of upper extremity provided by the combination of the motion of the shoulder joint and the shoulder girdle is 65% of a sphere. Denavit-Hartenberg (DH) [38,39] model of the arm is straightforward to derive. Upper limb is usually considered as a model with seven DOFs, three DOFs for shoulder, two DOFs for elbow and two DOFs for wrist. Figure 4 [24] depicts coordinate assignment for upper limb. Table 1 [24], lists DH parameters for arm segments. β is physiological ROM for the corresponding anatomical joint. a_i and d_i are body segment lengths that are constant for each individual scaled with the total height of the person. Table 2 [24,40] gives these anthropometric data. H, W represents the subject's body height and subject's weight, respectively. Table 3 [41] shows regression coefficients to calculate the moments of inertia for each segment of the upper limb. In this table the center of coordinate of each segment is chosen at the center of mass of that segment. *X* axis is defined in the frontal plane and its positive direction is from center to the front of the body. *Y* axis is defined in the sagittal plane and its positive direction is from the center to the left of the body. *Z* axis is defined in the horizontal plane and its positive direction is from center to the head. As an example to show how to use this table, suppose that we want to calculate the moment of inertia of hand about axis *z* using the last row of the table, the answer is as follows:

Table 2. Anthropometric data [24,40].

Body segment	Length, L	Weight of the segment	Center of mass (% of L) Proximal	Center of mass (% of L) Distal
Hand	0.108H	0.006 W	0.506	0.494
Forearm	0.146H	0.016 W	0.43	0.57
Upper arm	0.186H	0.028 W	0.436	0.564
Forearm and hand	0.254H	0.022 W	0.682	0.318
Upper limb	0.44H	0.05 W	0.53	0.47

$$-6.26 + 0.0762\text{W (kg)} + 0.0347\text{H (cm)} \tag{1}$$

Dynamics of upper limb

The most common method to determine human body dynamics is the inverse dynamics approach. Inverse dynamics is a method for deriving the internal torques (τ) and forces in each joint from the motion data.

Body motion can be formulated using Lagrange-Euler formulation [38,39]:

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{K}(\mathbf{q}) = \boldsymbol{\tau} \tag{2}$$

$\mathbf{q}$ is generalized coordinates, $\mathbf{M(q)}$ is mass moment of the inertia matrix. $\mathbf{C}(\mathbf{q},\dot{\mathbf{q}})$ is coriolis and centrifugal forces. $\mathbf{K(q)}$, is gravity term and τ is generalized torque applied on each segment.

Developing a rehabilitation robot requires a profound understanding of the kinematics and dynamics of the human arm during ADL and is beyond the anthropometric information that has been widely known for decades. Jacob Rosen et al. in 2005 at the University of Washington conducted a research to acquire human arm kinematics and dynamics during daily activities [42]. They conducted this research during designing a seven DOF upper limb powered exoskeleton. Kinematics of the upper limb is acquired with a motion capture system while performing wide variety of daily activities. Human arm dynamics is studied using analytical and numerical approaches. They also concluded that various joint kinematics and dynamics change significantly based on the nature of the task [24,26].

Table 3. Regression coefficients for moment of inertia of upper limb [41].

Body segment	Constant	Coefficient of the person's weight	Coefficient of the person's height
Moment of inertia about x (kg cm^2)			
Upper arm	−250.7	1.56	0.62
Forearm	−64	0.95	0.71
Hand	−19.5	0.17	0.5
Moment of inertia about y (kg cm^2)			
Upper arm	−232	1.525	1.343
Forearm	−67.9	0.855	0.376
Hand	−13.68	0.088	0.092
Moment of inertia about z (kg cm^2)			
Upper arm	−16.9	0.662	0.0435
Forearm	5.66	0.306	−0.088
Hand	−6.26	0.0762	0.0347

Literature review

Up to this point, the basics of rehabilitation robots have been introduced. Next, the most prominent works in rehabilitation robotics is stated. Lots of researchers around the world have developed some robots for rehabilitation of upper limb.

MIT-MANUS

Technical aspects

MIT-MANUS [32] is one of the very first robots developed for rehabilitation. The project was initiated in 1989 and has been in daily operation since 1994. Figure 5 [right (up)] [37] depicts the commercial version of MIT-MANUS called Inmotion2. The most prominent feature of this robot which is also available commercially is being modular. Its different modules can be operated in a stand-alone or a system fashion. This feature is really useful, because only needed part of affected upper limb can be treated. The robot incorporates four modules: a planar two-DOF active module, a vertical one-DOF active module, a three-DOF active wrist module and a one-DOF passive grasp module. The planar

Figure 5. MIME system [53] (left), Inmotion2 (the commercial version of MIT-MANUS) [37]) [right (up)] and GENTLE/s system [55] [right (down)].

two-DOF active module is limited to horizontal movements with gravity compensation and is used for performance based training. It provides two translational DOFs for elbow and forearm motion. It is portable and consists of a direct-drive five bar linkage SCARA (Selective Compliance Assembly Robot Arm) type manipulator. This configuration is selected due to its low impedance on the vertical axis. This feature provides a back-drivable robot to easily carry the weight of the patient's arm. The mechanism is driven by brushless motors with absolute encoders for position and velocity measurements. Redundant velocity measurements are provided by using DC tachometers. A six DOF force sensor mounted on robot's end-effector measures the interaction forces between the human and the robot. A personal computer is used to both implement control architecture and display the task to both the operator and the patient via monitors. Custom-made hand holders connect the patient's upper limb to the robot end-effector. The vertical one-DOF module provides vertical motion and force. Two prototypes were developed for vertical module. First a screw-driven module was developed at MIT late 2000. By recent advances in linear motor technology, a linear direct-drive module was developed and used. Unlike most industrial robots, MIT-MANUS has safe and stable operation in close contact with humans and is specially designed and built for clinical rehabilitation applications. This is achieved by using backdrivable hardware and impedance control. It has low intrinsic end point impedance so it is backdrivable. It has low inertia and low friction. The three-DOF wrist module [29] was introduced to MIT-MANUS after its successful clinical results in rehabilitation of elbow and shoulder [43]. The first clinical results with this module [44] showed that it provides an effective means for wrist rehabilitation. The wrist module mounts on the end of the planar module and incorporates a magnetic lock for safety and quick connection and disconnection. The sensorimotor training provided by this robot is by using video games. The patient should move the robot end-effector according to the game's goals. If the patient cannot perform the task, the robot will assist and guide the patient's hand. This robot can be categorized as end-effector-based robots.

Clinical outcomes

Clinical outcomes with MIT-MANUS and Inmotion2 are promising. Several random controlled trials (RCTs) have been conducted that statistically showed considerable reduction in shoulder and elbow impairment from the beginning of robotic rehabilitation to the end of it. This reduction in impairment is shown for acute, sub-acute and chronic patients. On the other hand, no considerable increase in functional performance is statistically shown [43–48]. The number of participant in the study varied from 20 to 127. Rehabilitation using MIT-MANUS showed considerable increase in comparison to Group therapy and intensive traditional therapy [49,50]. A multi-center RCT study showed that MIT-MANUS did not show considerable results after 12 weeks in comparison to usual and intensive therapy, but after 3 months follow-up showed considerable results in comparison to usual and not intensive therapy [51].

Mirror image motion enabler

Technical aspects

Mirror Image Motion Enabler (MIME) [52–54] was initiated in 1998 and was first tested in 2002. The device is designed for shoulder and elbow neurorehabilitation. Figure 5 (left) [53] depicts MIME system. The initial prototype incorporated a Puma 260 robot, but the current system incorporates a Puma 560 robot that applies forces to the paretic limb during unilateral and bilateral movements in 3D. Subjects are seated in a wheelchair in front of a height-adjustable table with straps limited torso movements. The affected limb is fastened to a forearm splint that restricts wrist and hand movement. A six-DOF robot manipulator (Puma 560, Staubli Unimation Inc, Duncan, South Carolina) is attached to the splint and applies forces to the limb. A six-axis sensor measures forces and torques between the robot and the affected limb. It has four modes of operation: passive mode, active-assisted mode, active-resisted mode and bilateral mode which is unique to MIME. In bilateral mode the subject attempts bilateral mirror image movements, while the robot assists the affected limb by moving the affected forearm to the contralateral forearm's mirror image position and orientation. The two forearms are kept in mirror symmetry using a position digitizer which measures the movement of the contralateral forearm and provides coordinates for the robot motion controller. Bilateral mode enhances the effects of the more conventional unilateral mode. The unilateral mode targets corticospinal pathways from the contralateral damaged cortical hemisphere, while the bilateral mode also involves the undamaged hemisphere. The bilateral mode may facilitate corticospinal ipsilateral pathways or the damaged pathways. All or some of these pathways might contribute to motor recovery after stroke. One disadvantageous feature of this system is that, since human upper limb is at least seven DOFs and the robotic manipulator is six DOFs, only the intersection of human limb workspace and robot workspace is reachable. Another disadvantage is that, since Puma 560 is an industrial robot and industrial robots are designed to work in industrial environment, they are not that safe to interact with humans. MIME can be classified into end-effector-based robots.

Clinical outcomes

In two RCTs, it was shown that MIME can improve impairment and muscle activation in sub-acute and chronic stroke patients [52,53]. In one study, 27 chronic stroke patients participated and in the other, 30 sub-acute stroke patients participated. One study showed considerable statistical improvement for MIME group in comparison to control group under Conventional Neurodevelopment Treatment (NDT), although after 7 months following this study, these differences faded [52]. Once unilateral mode is compared with bilateral mode, it is demonstrated that unilateral mode and combined (unilateral and bilateral) showed considerable improvement in comparison to NDT control group and bilateral mode [53].

GENTLE/s

Technical aspects

Loureiro et al. in 2003 introduced GENTLE/s system. GENTLE/s [55] is a system based on haptics and VR visualization techniques. Haptics is the study of integrating tactile and other sensors into meaningful manner and haptic interfaces are group of robots that incorporate haptics and VR technology. The advantage of using such systems is that they attract patient's attention and motivates him/her to exercise for longer periods of time. According to the study by Coote et al. [56], during functional exercise post-stroke, the haptic and visual feedback of the robotic system has a more positive treatment effect than single-plane, repetitive exercises. GENTLE/s system incorporates a three-DOF haptic master in order to provide a haptic interface. The haptic master can provide reaching movements in three active DOFs. This couples to three passive DOFs to allow arbitrary positioning of the person's hand, so the overall DOFs are six (three passive and three active). Figure 5 [right (down)] [55] shows GENTLE/s setup. The patient is seated on a chair with his/her arm suspended to eliminate the effects of gravity. The wrist is placed in a wrist orthosis and is connected to haptic interface using a magnetic safety connection to prevent excessive force being applied to the arm. The therapist based on the patient's profile chooses the right exercise for the patient using a 3D graphical user interface (GUI). Games incorporated in GENTLE/s system, consist of minimum jerk paths between a starting and ending point. It is proved that creation of human-like trajectories is essential for training upper-limb movements after stroke. Human by nature tend to minimize jerk parameter over the duration of the reaching movement of the arm. Jerk is the rate of the change of acceleration with respect to time. GENTLE/s includes three therapy modes: passive mode, active-assisted mode and active-resisted mode. GENTLE/s can be classified into end-effector-based robots. A study [56] proved that, robot-mediated therapy using GENTLE/s system have a treatment effect greater than the same duration of non-functional exercise. The Arm Coordination Training robot (ACT 3D [57]) is developed based on the aspects of GENTLE/s system. ACT 3D robot targets abnormal joint torque coupling between the elbow and shoulder joint.

Clinical outcomes

Coote et al. conducted a research on 20 chronic stroke patients using GENTLE/s and arm in a sling in two ABC (baseline-rehabilitation with GENTLE/s-rehabilitation with arm in a sling) and ACB studies. This study proved that patients who used the robotic system had higher improvement rate in robotic rehabilitation phase than arm in a sling phase or baseline phase [56].

Bi-Manu-track

Technical aspects

Hesse et al. developed a robot-assisted arm trainer, Bi-Manu-Track [28]. The one-DOF device is designed for bilateral passive and active practice of forearm pronation/supination and wrist flexion/extension. For smooth movement, impedance control is implemented. It has three operational modes: passive, bilateral active-assisted mode and bilateral active-resisted mode. The advantageous features of this device are being portable, simple, low-cost and its bilateral exercises, because using non-affected limb may stimulate ipsilateral corticospinal projections to the paretic muscles. Figure 6 [left (up) and left (down)] [28] shows bilateral pronation/supination of the forearm and bilateral flexion/extension of the wrist. Subjects sat at a table with their elbows bent 90 degrees and put their forearms in the midposition between pronation and supination. Each hand grasps a handle. The handles are connected by an axis linked to the respective electric motor. The device incorporates two handle sets, one with a horizontal axis of rotation for the elbow and one with a vertical axis for the wrist movement. Motor drives are position controlled and a display shows the number of performed cycles to motivate the patient to exercise more. Bi-Manu-Track is classified into end-effector-based robots.

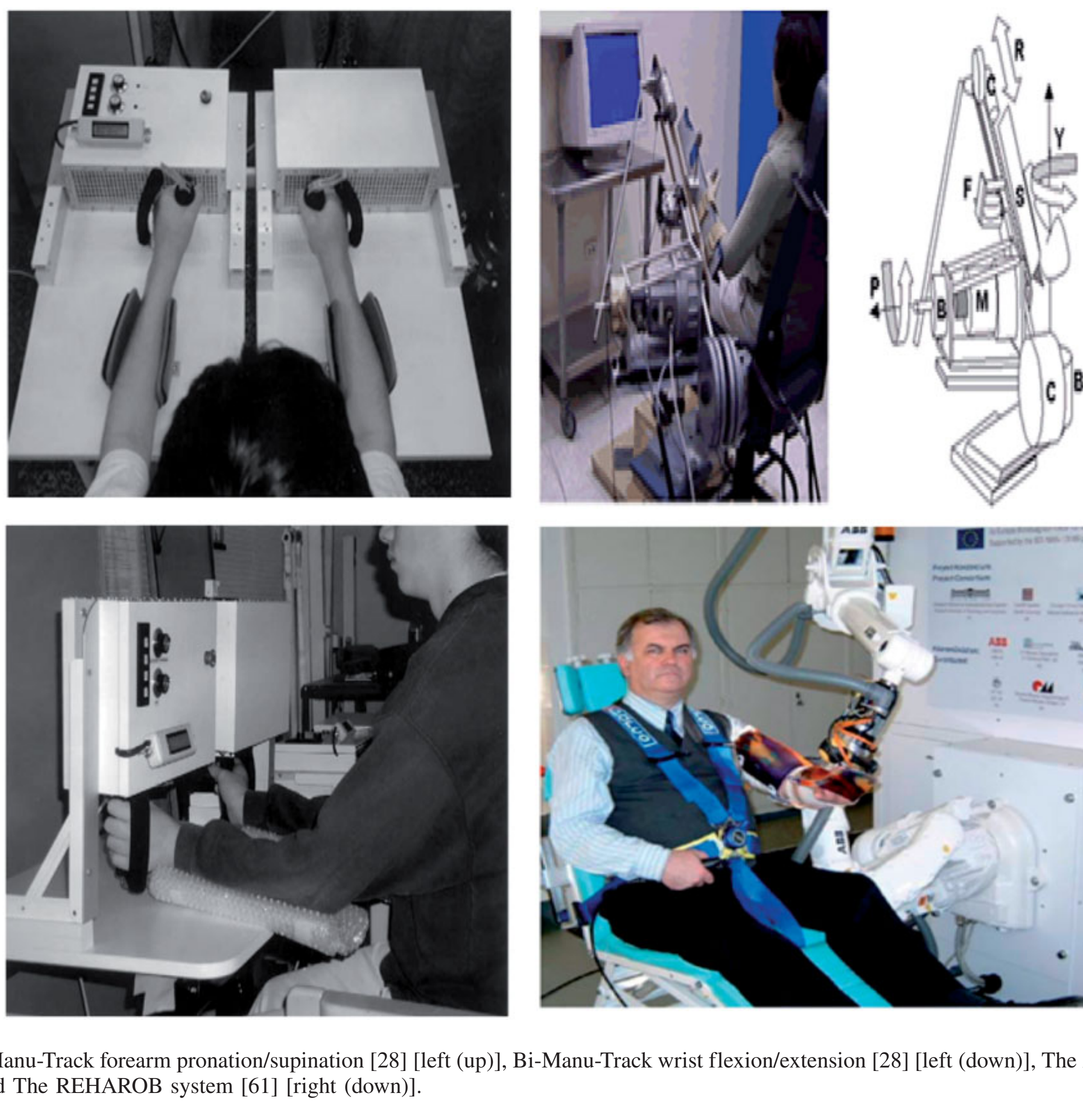

Figure 6. Bi-Manu-Track forearm pronation/supination [28] [left (up)], Bi-Manu-Track wrist flexion/extension [28] [left (down)], The ARM guide [58] [right (up)] and The REHAROB system [61] [right (down)].

Clinical outcomes

Bi-Manu-Track was tested on chronic stroke patients and this study showed improvement in 5 of 12 patients. Muscle tone is also improved in 8 of 12 subjects, although this motor improvement cannot be translated into better functional performance in ADL [28]. This study lacked control group and patients were also involved in other rehabilitation programs [28]. An RCT study was conducted on 44 sub-acute stroke patients. In this study, one group used Bi-Manu-Track and the other group were under Electrical Stimulation Therapy (both groups were also involved in conventional therapy at the same time). It was proved that impairment scores for both groups were improved, although Bi-Manu-Track group showed more improvement. 6 months follow-up there was no difference between the two groups [30].

Assisted rehabilitation and measurement guide

Technical aspects

Reinkensmeyer et al. developed Assisted Rehabilitation and Measurement (ARM) guide [58] to assess and train arm movement impairments following stroke and other brain injuries. It is used both as a diagnostic tool for several motor impairments and as a therapy tool. Figure 6 [right (up)] [58] depicts the ARM guide. The patient's arm is fastened to a splint that slides along a linear bearing. A motor assists or resists arm movement along the bearing. To apply forces to the arm, the motor drives a chain drive attached to the splint. An optical encoder attached to the motor measures the arm position. A six-axis load cell between the splint and the linear constraint measures the forces generated by the arm. The main movement of the robot is to help the arm in reaching movement which is a fundamental movement in ADL. The orientation of the linear bearing can be changed in the vertical and horizontal planes and locked with computer-controlled magnetic particle brakes, allowing reaching at different elevation and yaw angles. The device is counterbalanced such that the splint remains at any position and orientation that is placed. As a result, the user would feel no spastic loading of the arm due to the weight of the device. There is a video monitor that gives the user feedback about the movement and force generation of the arm. The mechanical structure of the device which is shown in Figure 6 [right (up)] [58] consists of a splint (S), a motor (M), a brake (B), a force/torque sensor (F) and a counter-balance (C). The device has one active and two passive DOFs. The three DOFs of the robot are: reach (R) which is actuated by the motor, yaw (Y) which is actuated by a brake and pitch (P) which is actuated by the brake. The advantageous feature of the robot is that because of using only one motor, the overall robot is simple and inexpensive. In a study by Reinkensmeyer et al. [58], the authors thoroughly expressed how to assess and train the hemiparetic arm with the ARM guide. The first version of ARM guide which was developed in 1999 was solely a passive device. The extended version which is now available and used incorporates a DC servo motor and is an active device. ARM guide can be classified as end-effector-based systems.

Clinical outcomes

Initial tests with the ARM guide demonstrated that it can detect workplace deficits, although it is unable to accurately measure the constraint forces induced by mismatching between ARM guide geometry and usual reaching movement [59]. In a pilot study, three chronic stroke patients trained with the ARM guide in active-assisted mode. In this limited study, ROM and muscle tone of two of three patients recovered. In one patient, there was no improvement in coordination and free reaching movement [58]. In one RCT study, Kahn proved that there is no discrepancy in chronic stroke patients using ARM guide and those under reaching exercise [60].

REHAROB

Technical aspects

Toth et al. developed REHAROB therapy system [61] to provide passive physiotherapy of spastic hemiparetic arm. Because human upper limb has at least seven DOFs and most industrial robots are of six or fewer DOFs, so REHAROB system utilizes two industrial robots, one robot moves the upper arm and the other robot moves the lower arm. REHAROB system performs the exercise according to the directions of the therapist. The therapist grasps the arm of the patient and moves it freely. The robot follows the patient's arm, while the controller memorized the motion trajectories. The REHAROB project was designed and built over a three-year period and was completed in 2003. Figure 6 [right (down)] [61] depicts REHAROB therapy system. The disadvantageous feature of this system is that REHAROB utilizes two industrial robots. Industrial robots are developed to work in industrial situations and are not safe to interact closely with humans. REHAROB system is classified into end-effector-based rehabilitation robots.

Clinical outcomes

Few clinical results are recorded using this robot. In usability testing, it is shown that constantly pressing the enabling device is tiring for patients [62]. On the other hand, safety mechanism is switched off suddenly and robot's resistance to training phase is high [63]. Four healthy subjects and eight patients went under robotic training that showed significant improvement in functionality and spasticity [63].

Robots that have been introduced up to now were all end-effector-based robots. Exoskeleton robots also exist that are designed for rehabilitation. Some of these robots will be stated next.

Dampace

Technical aspects

Stienen et al. in 2007 developed a dynamic force-coordinator trainer for the upper extremities called Dampace [35]. It stands for Damped Space or Pace. Dampace is a passive exoskeleton that incorporates controlled braking on the three rotational axes of the shoulder and one axis of the elbow. Controlled braking instead of actively assisting actuators has the advantage of inherent safety and patients always participate actively in the movement, but with the disadvantage of not being able to assist movements and creating all virtual environments. Only those virtual environments that do not need energy being put into the system can be created. The most prominent feature of Dampace is that, the axes of Dampace do not necessarily need to align with the human shoulder and elbow axes. Human shoulder joint does not only have three rotational DOFs but also it has two translational DOFs. Dampace utilizes this feature and by allowing some additional mobility in the shoulder and elbow joints, overcomes the traditional difficulty of necessity of perfectly aligning the exoskeleton axes with those of human joint axes. In the case of misalignment, if reaction forces occur, exoskeleton moves in the translational DOFs until the force is gone. So Dampace can be considered as auto-aligning exoskeleton with controlled resistance around the joint axes. It has a separate gravity compensation system. The rotations of the three joint axes of the shoulder and the one of the elbow can be actively resisted by powering the hydraulic disk brakes. A feedback controller analyzes the

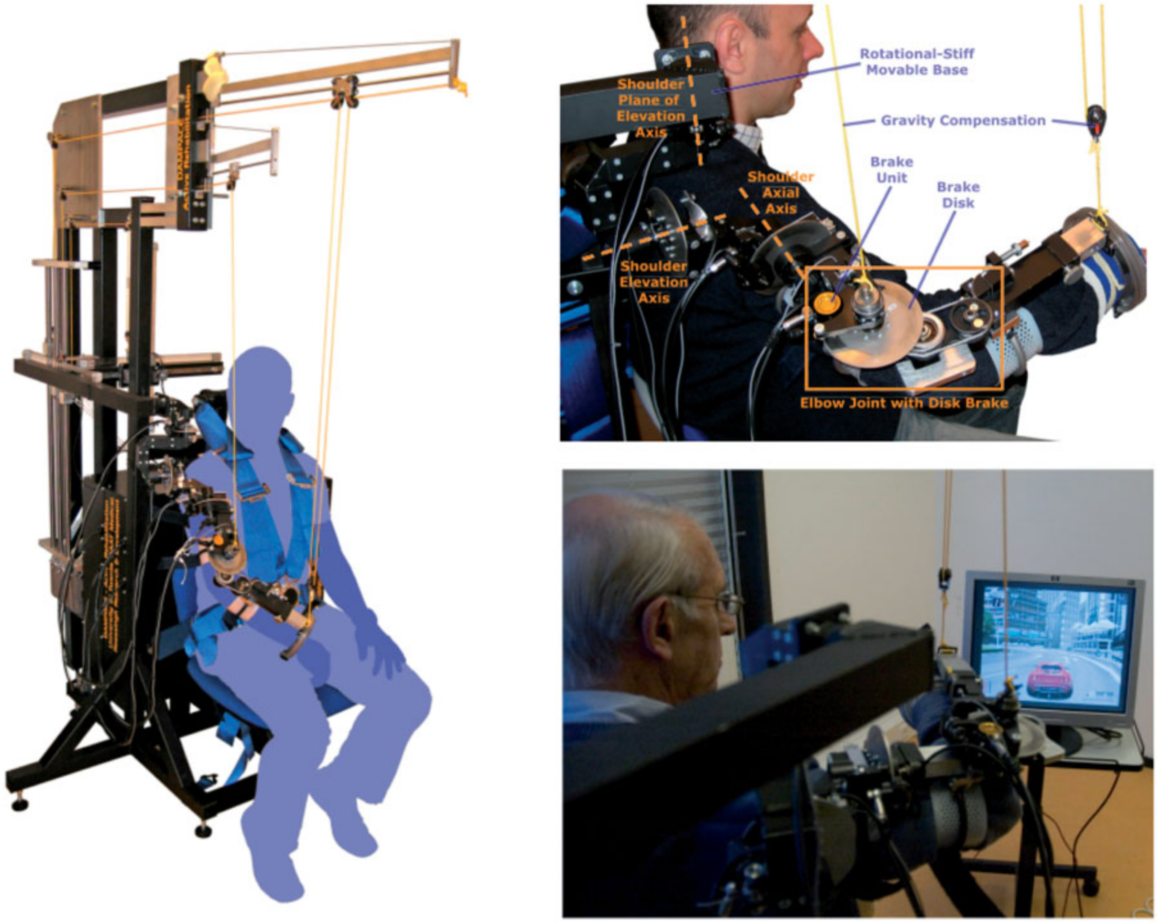

Figure 7. The Dampace system [35] [left and right (up)], Interfacing Dampace with a game console [35] [right (down)].

measured rotation angles and joint torques of the four axes and applies resistance torques to the joints based on these measurements. Figure 7 [left and right (up)] [35] depicts Dampace system. To motivate subjects, human movement and force execution are linked to a gaming console. Figure 7 [right (down)] [35] depicts a person performing a game.

Clinical outcomes

No clinical outcomes using Dampace have been reported to date.

T-WREX

Technical aspects

Sanchez et al. developed T-WREX [64] or therapy WREX system. The T-WREX system consists of an arm orthosis, a grip sensor that detects hand grip pressure and software that simulates functional activities. T-WREX is an instrumented with position sensors, adult-sized version of Wilmington Robotic Exoskeleton (WREX) which is a five DOF system that passively and partially counterbalances the weight of the arm using elastic bands. T-WREX actually developed to be a 3D input device to interact with virtual environments. T-WREX system can be considered to be an extension to Java Therapy. In Java therapy, the patient will log into a website and perform a customized program of therapeutic activities by using a mouse or joystick as an input device. Using mouse or joy stick as an input device limits the functional relevance of the system. So T-WREX system was developed as an input device that allows a broader range of functional arm movements to be practiced and monitored. T-WREX system can be flipped for use with left or right arm. The system allows a therapist to supervise several patients at a time for group therapy sessions or used at home. Figure 8 [left (up)] [64] depicts T-WREX mechanical design and its ROM with a person using it. Housman et al. in 2009 conducted a research [36] that proved that gravity-supported arm exercise using T-WREX can improve arm movement ability after chronic severe hemiparesis. T-WREX is now commercially available as Armeo Spring. The Armeo Spring system works without any motors. It has a complete exoskeleton structure. Springs support the human arm against gravity.

Clinical outcomes

Clinical tests conducted on chronic stroke patients represented that this robot can be compared with conventional weight-bearing exercise in impairment reduction and increase in using the impaired limb. A study conducted on 23 patients compared T-WREX with conventional self-directed exercises. Although the group using T-WREX was superior in terms of arm movement mobility, this group was not significantly higher than the control group [65]. Another RCT including 28 patients displayed that patients using T-WREX showed more improvements than tabletop support patients. On the other hand, the group using T-WREX had better impairment scores after 6 months following treatment. Qualitatively, patients preferred T-WREX to conventional therapies [66].

MGA-exoskeleton

Technical aspects

Carignan and Lizka in 2005 developed an arm exoskeleton named Maryland-Georgetown-Army (MGA) exoskeleton. MGA-exoskeleton [26] incorporates five active DOFs for shoulder and

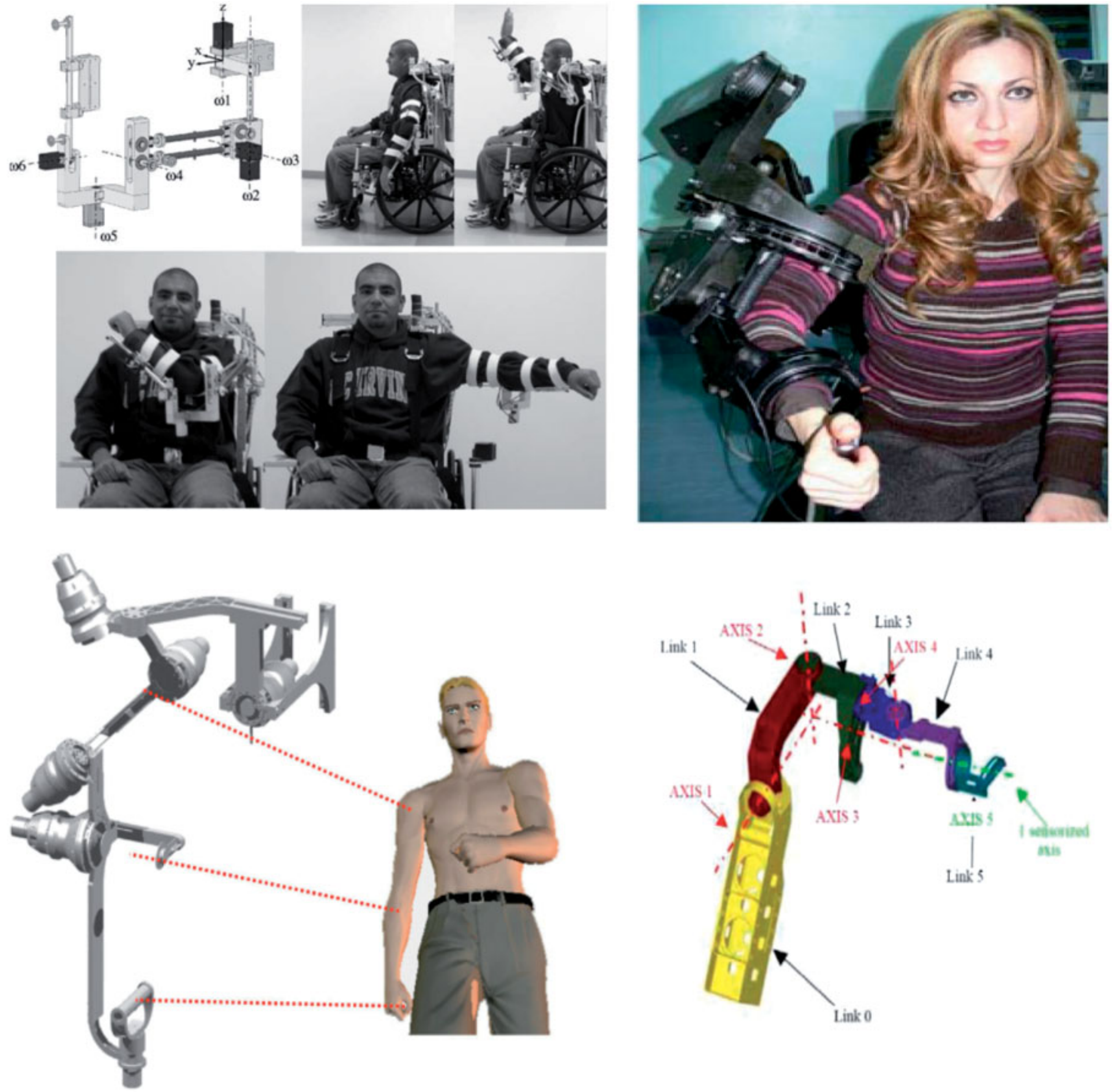

Figure 8. T-WREX system [64] [left (up)], MGA-exoskeleton [26] [left (down)], L-EXOS system [67] [right (up)], L-EXOS mechanical structure [67] [right (down)].

elbow motion. Three DOFs is assigned for shoulder rotation, one DOF for elbow actuation and one active DOF for scapula motion. First two prototypes of this exoskeleton were built. The first prototype was mainly used to evaluate the kinematics and to decide what passive link adjustments would be required. After optimization, the final design depicted in Figure 8 [left (down)] [26] was built. Each joint of the exoskeleton except for the forearm is driven by brushless DC motors and harmonic drive transmission. The elbow is equipped with a clutch that has an adjustable torque range which decouples the elbow axis from actuator in the case of applying excessive torque to the elbow joint. Motor position is determined by optical incremental encoders and at the output of the transmission, optical absolute encoders determine absolute position on startup and monitor the incremental encoders. A force/torque sensor measures forces and torques on the handle. A single-axis torque sensor is placed on the output side of the scapula transmission. Two single-axis load cells are attached to mounting plates on either side of the elbow to measure axial load at the elbow. The exoskeleton operates in two modes: (1) VR mode and (2) physical therapy mode. In the first mode, the forces exerted at the hand are sensed by a force sensor located at the hand gripper and controlled by interaction with a virtual environment generated by a computer. Computer-generated environment simulates daily living tasks for functional rehabilitation. The control architecture used in this mode is admittance control. Admittance controller converts the sensed contact forces at the hand and elbow into desired movement of the exoskeleton. In the second mode, the arm is allowed to rotate about an arbitrary axis through the shoulder using a resistance profile. In fact, the exoskeleton becomes a programmable resistance trainer. The control architecture used in this mode is impedance control. The scapula joint is controlled independently from other arm joints. The controller used for scapula motion is admittance controller. A torque cell at the output of the transmission, directly measures the torque being exerted by the scapula joint. Safety decisions are carried out with the robot control computer. The therapist can adjust the spring length and select the proper amount of support. Sensors measure the position and orientation of the human arm and transmit them to the graphical display in which the patient can see his/her own movement on the computer screen.

Clinical outcomes

No clinical outcomes using MGA-exoskeleton has been reported up to now.

L-EXOS

Technical aspects

Frisoli et al. in 2007, developed a robotic exoskeleton named L-EXOS [67] system, a force feedback exoskeleton for the right arm. L-EXOS stands for light exoskeleton. The exoskeleton is capable of providing a controllable force at the center of user's right hand palm. Figure 8 [right (up) and right (down)] [67] depicts L-EXOS system worn by user and its mechanical structure, respectively. A button placed on the handle allows performing basic selection operations in the virtual environment. L-EXOS is a serial five DOFs robot, four of which are actuated and sensorized and last DOF which provides wrist pronation/supination is only sensorized. First three rotational axes are incident and mutually orthogonal, i.e. spherical joint with the same center of rotation of the human shoulder. While human shoulder joint is not a perfect spherical joint, its center may vary with respect to different arm postures. This drawback is overcome in L-EXOS by not physically constraining the shoulder to the exoskeleton device allowing a greater motion freedom while performing a required task. The most prominent feature of this exoskeleton is its light weight due to placing its high torque motors at the base of the exoskeleton. This remote placement of motors will highly reduce the perceived inertia by the user at the palm. The system is light weight and highly backdrivable due to remote placement of motors and using cable transmission instead of gear transmission. The L-EXOS system has an integrated video projection system for visualization of the virtual environment. Tasks that are performed in VR environment consist of a reaching task in which the patient actively conduct the task and is passively guided by the robot when he/she cannot perform it, a free motion task in which the patient moves freely along a circular trajectory and a task of object manipulation in which the patient is asked to move cubes represented in the virtual environment and arrange them in an order decided by the therapist. All contact forces can be perceived during the simulation. The control scheme used in reaching task is impedance control.

Clinical outcomes

No clinical outcomes using L-EXOS have been recorded until now.

ARMin

Technical aspects

One of the most advanced exoskeleton robots in arm rehabilitation until now is the arm therapy, ARMin. The project was initiated in 2003 by Nef et al. Armin I [68–70] was designed and tested from 2003 to 2006. It had four DOFs, actuating the shoulder in 3D and flexing/extending the elbow. Figure 9 [left (down)] [68] depicts ARMin I robot. The upper arm is connected to the robot by an end-effector-based structure and the lower arm is connected through an exoskeleton structure. So, ARMin I can be considered as semi-exoskeleton robot. It incorporated three modes of operation: (1) passive mobilization, (2) active game-supported arm therapy and (3) active training of ADL. After ARMin I, ARMin II [71] is developed with a complete exoskeleton structure and two additional DOFs (six altogether). The additional DOFs are for lower arm pronation/supination and wrist flexion/extension. In this version, the shoulder actuation is optimized by sophisticated coupling mechanism enabling the center of rotation of the shoulder to move in a vertical direction when the arm is lifted providing 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 [72]. Figure 9 [right (up)] [71] depicts the ARMin II setup. ARMin III [73–76] is a further improved version of ARMin II in the case of robustness, complexity, user operation and reliability. Five ARMin III devices were developed for a multicenter clinical trial. In this version, three electric motors actuate the shoulder joint for shoulder flexion/extension, abduction/adduction and internal and external rotation. Two motors actuate the elbow joint for elbow flexion/extension and forearm pronation/supination and one motor actuates wrist for wrist flexion/extension. An optional module is incorporated for hand opening and closing. The motors are equipped with two position sensors for redundant measurements. Motors and gears are carefully selected for low friction, good backdrivability which is an important requirement for sensorless force control [77]. Impedance control strategy [77,78] allows implementing patient-responsive control in which the patient is being assisted only as much as needed. Figure 9 [right (down)] [71] depicts ARMin III setup. 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. The lengths of the upper and lower arms are also adjustable. Laser pointers indicating the center of the glenohumeral joint help the therapist position the patient in the ARMin III device. The robot can be configured to use with the left or right arm. A spring in the uppermost horizontal robotic link compensates for part of the weight of the exoskeleton. This is crucial for safety reasons especially when the power is off, it can balance the robotic arm. Therapy modes implemented on ARMin III are: (1) passive and active mobilization in which the robot moves the patient's arm on a predefined trajectory. Figure 10 (right) [74] demonstrates trajectories for passive mobilization. The thin lines show the recorded trajectories and the thick lines represent the smooth trajectories repeated by the robot. The robot is position-controlled. The control architecture for mobilization therapy is computed torque position control. Regardless of what the patient is doing, the robot will follow the predefined trajectory because, feedback loops help the motors compensate for any resistance the patient produces. If the patient moves together with the robot in the desired direction, it is called active mobilization; in this case motors have less work if the patient remains passive, which is called passive mobilization. As it is desirable that the patient actively contributes to the movement, motor torque can be used as a performance measure to monitor how actively the patient contributes to the movement. The audio–visual display gives feedback on the performance of the patient. This position controlled training requires predefined trajectories. The therapist can either input data via a computer GUI or use a known teach-and-repeat procedure in which the therapist moves the robotic arm together with the human arm in the desired way and the robot records store the position data to repeat the movement shown by the therapist, (2) game therapy: computer games and VR technology are good ways to motivate the patient to participate actively in the training. Implemented games to date are: ball game, labyrinth and Ping-Pong game. The control strategy used here is assist-as-much-as-needed control paradigm. It means that if the patient can perform the task, the robot does not deliver any support, if not the robot supports the patient with an adjustable force that pushes or pulls the hand to the appropriate position, and (3) training of ADL: the purpose of ADL training is to stimulate real-life tasks to further motivate the patient. ADL training is presented on the computer screen and the patient tries to complete the task. The robot supports the patient as much as needed and

Figure 9. ARMin I robot [68] [left (down)], ARMin II setup [71] (left (up) and ARMin III setup with a person performing an ADL task with it [71] [right (up)].

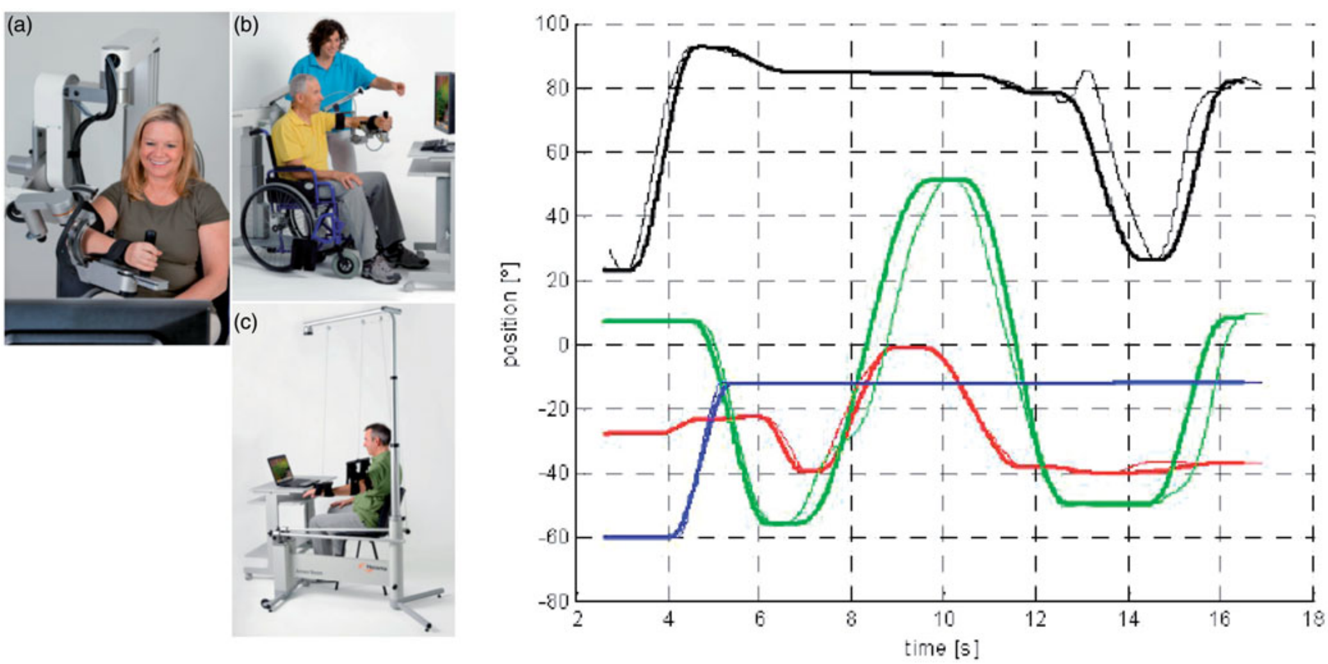

Figure 10. (Left) (a) Armeo Power, (b) Armeo Spring and (c) Armeo Boom [23] and Teach-and-repeat trajectories for passive mobilization (right) [74].

interferes only if necessary. Implemented ADL tasks to date are setting the table, cooking potatoes, filling a cup, cleaning a table, washing hands, playing the piano and manipulating an automatic ticketing machine. ARMin III can give a quantitative measure of some parameters such as active and passive ROM, muscle strength, abnormal joint synergies [79] and spatial precision of hand positioning. Measured technical data for ARMin III robot is presented in [23]. ARMin is commercialized by the name of

Armeo Power (Figure 10 (left a) [23]). The Armeo product line, HOCOMA, Switzerland, is composed of three products which are optimized for a specific phase of the rehabilitation process: Armeo Power (the commercialized version of ARMin III), Armeo Spring (Figure 10 (left b) [23]) and Armeo Boom (Figure 10 (left c) [23]). Shortly after injury, the patient with no or very little voluntary activation of arm muscles trains with the motorized robotic device, Armeo Power (former ARMin III). Once his/her motor function improves and some active movements are possible, the patient continues arm training with the non-motorized, weight-supported exoskeleton Armeo Spring (former T-WREX). After further improvements, training with Armeo Boom starts and consists of an overhead sling suspension system, which is suitable for patients who can actively move the arm but suffer from reduced workspace and poor motor control. To date, several studies are conducted to evaluate the efficacy of ARMin in arm rehabilitation progress. Staulbi et al. conducted a research on investigating the effects of intensive arm training on motor performance in four chronic stroke patients using the robot ARMin II [80]. 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 in a chronic stroke.

Clinical outcomes

In a usability pilot study with healthy subjects, eight stroke patients and three spinal cord injury patients showed that subjects could perform the exercises easily and had a positive view on ARMin. Yet, there were some problems with device's fixation (it took about 5 min) and subjects with unstable shoulder joints could not be treated with robot. ARMin II solved this issue by moving the shoulder in correct anatomical places. In a pilot study, four chronic patients went under treatment using ARMin II. Three of the four subjects demonstrated significant improvement in the Fugl–Meyer Assessment Scale Score for upper limb and this continued up to 6 months following treatment. Yet, subjects were not able to translate improvement in motor performance to ADL [80].

Jingguo Wang and Yangmin Li introduced a hybrid impedance control for a three-DOF robotic arm connected with haptic virtual environment for rehabilitation therapy assisting stroke survivors [81], in which both the position and the force trajectories are controlled. Their results showed that the proposed control method can track both the position and force trajectory well. Review of control strategies used in rehabilitation robots is given in reference [82]. Table 4 summarizes the important information presented until now.

Discussion

Considering the literature review presented in the previous sections, it is obvious that there are many robots built for rehabilitation. On the other hand, few of these devices are available commercially and those that are available are not commonly used in clinics and hospitals and even less are used at homes [83]. This issue is due to factors such as lack of clinical evidence, limited functionality, cost constraints, safety concerns, equipment size and usability issues [83].

Functionality is an important factor in rehabilitation robotics. End-effector-based robots have less functionality than exoskeleton robots since they have two or three DOFs and this limits simulation of ADLs. Exoskeleton-based robots have more flexibility and ROM. Devices that utilize more senses are more welcome, for example audiovisual displays and haptic displays.

Clinicians will accept rehabilitation devices when they prove their efficacy in rehabilitation more than conventional techniques [84]. Many devices that have been reviewed until now had RCTs; among these, MIT-MANUS, MIME and Bi-Manu-Track showed statistically significant improvements in studies. More clinical tests should be done using other devices to prove their clinical advantages. Kwakkel has done a meta-analysis on upper-limb rehabilitation devices which indicated a significant moderate summary effect size in upper-arm robotic rehabilitation with an overall change of 7–8% in motor control based on Fugl–Meyer assessment scale and Chedoke–McMaster Stroke Assessment Scale (assessment tools used to measure impairment and disability in those with neurological impairments) [21]. However, there was no significant improvement on ADL outcome based on the Functional Independence Measure (an assessment tool used to measure functional outcomes).

Safety issues are also important. These become more important when the patients use the device without the help of a supervisor. There are a lot of factors that are involved in device's safety. Generally, backdrivable impedance controlled devices are safer than admittance controlled devices. Haptic devices that are impedance controlled have less hard virtual surfaces than admittance controlled devices and are suitable for simulating free air. Passive devices (non-actuated devices) are generally safer than active devices (actuated devices) that are more prone to fail. End-effector-based devices have excessive freedom for shoulder joint and cannot detect unnatural movements. Exoskeleton-based devices, on the other hand, can control each joint easily and independently. Yet, even using exoskeletons, if mismatching occurs, the arm will be positioned in unnatural state. Amount of force that the device can be exerted is another safety issue. It is important that the robotic device produces required amount of force and not more than that. This issue is more important for industrial robots that can exert a large amount of force.

Cost of the robotic device is another issue. The cost of robotic devices not only includes the initial development of the device, but also device's maintenance, training and therapist's set up time [85]. Devices with more DOFs have both high initial and maintenance costs that include maintaining motors and sensors. Some studies showed effectiveness of robotic devices in comparison to usual or intensive therapy techniques [36,52,86,87]. A lot of clinics and hospitals may prefer hiring a therapist than purchasing a rehabilitation device due to lower costs.

Rehabilitation robots should have a simple use. Usability includes ease of set up and intuitive user interfaces. End-effector-based robots have easier setup than exoskeleton-type robots. Devices that require therapist's programing are not welcome since they require more set up time. Devices that face set up problem in clinic cannot be used in homes either.

Accessibility to rehabilitation is one of the major motivations to develop these devices. For this reason, accessibility of the device to the stroke patient should be evaluated. Accessibility includes device's costs, portability and therapist's use. Portability is an important factor, i.e. when a stroke patient lives in far places, he/she cannot go to a clinic and hospital frequently. On the other hand, heavy devices cannot be used in clinics and homes.

Briefly, if these devices want to be put into practice, they should reduce the burden of therapist's job and they should also be low cost. Considerations such as good clinical outcome, functionality, DOFs, ROM, usability, safety and accessibility are important to design a device which will be used by the patient and therapist.

Conclusion

In the ''Introduction'' section of this article, the concept of stroke was defined and types of strokes were introduced. The rate of incidence of stroke in the world was also demonstrated.

Table 4. Rehabilitation robots – summary.

Robot's name	DOF(s)	Supported joints of upper limb	Sensors used	Actuators used	Control input	Control scheme	Type
MIT-MANUS (Inmotion2) [32]	7 (6 active, 1 passive)	Elbow, shoulder, wrist	absolute encoders, DC tachometers, six-DOF force sensor	brushless motors	Joint position, angular velocity and torque	Impedance control	End-effector-based
Mirror Image Motion Enabler (MIME) [52–54]	6 (6 active and 0 passive)	Shoulder, elbow	Six-axis force/torque sensor, position digitizer	DC brushed servo motors	Forearm position, orientation, torque	Not specified	End-effector-based
GENTLE/s [55]	6 (3 passive, 3 active)	Shoulder, elbow, forearm	Not specified	DC brushed motors	End-point torque, position and velocity	Bead pathway	End-effector based
Bi-Manu-Track [28]	1 (1 active and 0 passive)	Forearm, wrist	Not specified	electric motor	Not specified	impedance control	End-effector-based
ARM guide [58]	3 (1 active and 2 passive)	Shoulder, elbow	optical encoder, force/torque sensor	DC servo motor, magnetic particle brakes	Forearm position and torque	Not specified	End-effector-based
REHAROB [61]	12	Shoulder, elbow	Not specified	Electrical motors	End-point torques	Not specified	End-effector-based
Dampace [35]	4 (0 active and 4 passive)	Shoulder, elbow	Not specified	hydraulic disk brakes	rotation angles and joint torques	Controlled braking	Exoskeleton – type
T-WREX (Armeo Spring) [64]	5 (0 active and 5 passive)	Shoulder, elbow, fingers	grip sensor, position sensors	No motors (passive)	Joint angles, grasp force	Not specified	Exoskeleton – type
MGA-exoskeleton [26]	5 (5 active and 0 passive)	Shoulder, elbow and forearm	optical incremental encoders, optical absolute encoders, force/torque sensor, single-axis torque sensor, single-axis load cells	brushless DC motors	Joint torques	admittance control, impedance control	Exoskeleton – type
L-EXOS [67]	5 (4 active and 1 passive)	Shoulder, elbow and forearm	Force sensors	Electric motors	Joint angles	impedance control	Exoskeleton – type
ARMin (Armeo Power)	6 (6 active and 0 passive)	Shoulder, elbow, forearm and wrist	position sensors, force/torque sensors	DC motors	Joint angles, grasp force	Impedance control, computed torque position control	Exoskeleton – type

Then, it continued by stating the importance of robot-aided therapy and its advantage over manually-assisted therapy. Section ''Rehabilitation Robots'' consisted of three sub-parts. Section ''Classification of Rehabilitation Robots'' classified the rehabilitation robots and discussed their advantages and disadvantages. Section ''Training Modes in Rehabilitation Robots'' discussed training modes implemented in rehabilitation robots to date. Section ''Requirements for a rehabilitation robot'' represented the requirements for a rehabilitation robot from different aspects. Section ''Upper Limb Kinematics and Dynamics'' introduced upper-limb kinematics and dynamics which are essential when designing rehabilitation robots. The article continued in Section ''Literature Review'' with a review of the most profound and important works in rehabilitation robotics. It discussed their mechanical structure, implemented control schemes and therapy modes. It also offered the results of some clinical tests discussing the effects of using these robots with patients. The results were promising and proved that robot-aided therapy indeed had a greater influence than manually-assisted therapy. These clinical results are not sufficient and more research is needed to test these robots with patients. The main goal of robot-aided therapy is to provide a means for increasing exercise intensity, because according to literature, the type of therapy matters less than the exercise intensity. The intensity of exercises can be increased using VR technology and games that also motivate patients to exercise more. It is another challenging research area in rehabilitation robotics to introduce VR exercises and games that have high relevance to rehabilitation process. Another challenging research area is to introduce patient-responsive control paradigms that can assist the patient only as much as needed and will increase his/her motivation.

Declaration of interest

The authors declare no conflict of interests. The authors alone are responsible for the content and writing of this article.

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