Med Biol Eng Comput (2011) 49:1103–1118
DOI 10.1007/s11517-011-0797-0

SPECIAL ISSUE - REVIEW

Advances in upper limb stroke rehabilitation: a technology push

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Received: 23 February 2011 / Accepted: 26 June 2011 / Published online: 20 July 2011

Abstract Strokes affect thousands of people worldwide leaving sufferers with severe disabilities affecting their daily activities. In recent years, new rehabilitation techniques have emerged such as constraint-induced therapy, biofeedback therapy and robot-aided therapy. In particular, robotic techniques allow precise recording of movements and application of forces to the affected limb, making it a valuable tool for motor rehabilitation. In addition, robot-aided therapy can utilise visual cues conveyed on a computer screen to convert repetitive movement practice into an engaging task such as a game. Visual cues can also be used to control the information sent to the patient about exercise performance and to potentially address psychosomatic variables influencing therapy. This paper overviews the current state-of-the-art on upper limb robot-mediated therapy with a focal point on the technical requirements of robotic therapy devices leading to the development of upper limb rehabilitation techniques that facilitate reach-to-touch, fine motor control, whole-arm movements and promote rehabilitation beyond hospital stay. The reviewed literature suggest that while there is evidence supporting the use of this technology to reduce functional impairment, besides the technological push, the challenge ahead lies on provision of effective assessment of outcome and modalities that have a stronger impact transferring functional gains into functional independence.

Keywords Stroke · Neurorehabilitation · Sensorimotor control · Upper limb · Rehabilitation robotics

1 Introduction

Although an increased effort is made on the recovery process of patients following a stroke, economic pressures and lack of available human resources means that patients generally do not reach their full recovery potential when discharged from hospital following initial rehabilitation [11]. Although there is already evidence suggesting that the damaged motor system is able to reorganise in the presence of motor practice, optimal training methodologies promoting such reorganisation remain unclear due to discrepancies of current rehabilitation therapy, quantification of dosage and rehabilitation type. The recovery of upper limb function is particularly affected, as the initial challenge is to stabilise the trunk and relearn minimum independence levels through gait re-learning.

Robotic machines have been identified as a possible way to automate labour-intensive training paradigms, to improve patient access to therapy and to provide new tools for therapists. Several authors have already proposed the use of robots for the delivery of this type of physiotherapy. The

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first far-reaching study on the acceptance of robot technology in occupational therapy for both patients and therapists was done by Dijkers and colleagues with the aid of a simple therapy robot [22]. Dijkers's study reports a wide acceptance from both groups, together with a large number of valuable suggestions for improvements. The advantages of Dijkers's therapy include the availability of the robot to successively repeat movements without grievance, as well as the ability to record movements. Hogan at MIT [40] was among the first to exploit Dijkers's idea to assist stroke neurorehabilitation using dedicated robotic systems.

One of the challenges still present today is to how best use robotic technology to augment the physiotherapist's skills [35]. On the contrary to public perception, robotic technology aims to be an advanced tool available to the physiotherapist and not a replacement. A robotic system is very unlikely to be able to amass all the skills of a physiotherapist, but it will be very good at conducting comparatively simple repetitive and manually intensive therapies. In this context, the physiotherapist would be doing all the clinical decisions and when suitable, considered and executed on the robot.

The following sections of this paper discuss the technical requirements for robots delivering assistance to re-learning arm and hand movements following a stroke and present a simple classification based on the mechanical principle and the control scheme utilised. Based on this classification, a summary of available technologies used in clinical research is presented followed by an overview of some early and newer rehabilitation systems, highlighting clinical research outcomes, and potentials and shortcomings for home rehabilitation. The technology overview follows an analysis of outcomes and explores issues relating to metrics of recovery and clinical assessment practice.

2 Technical requirements

Rehabilitation robots for the upper limb can be classified as passive, where the system constrains the patient's arm to a determined range of motion (no actuation); active, where the system moves the patient's arm through a predefined path (electromechanical actuation, pneumatic, etc.); and interactive, which reacts to patient's inputs to provide an optimal assistance strategy [96]. Passive systems often consist of mechanical linkages that move easily when pushed. Active systems are operated using traditional position control schemes to take the patient's arm from a predefined position to a new position using a certain velocity profile. Interactive systems are usually backdriveable and possess low, intrinsic, end point impedance [40]. Such systems facilitate the creation of dynamic rehabilitation tasks and allow the measurement of subsequent effects following intervention. Non-backdriveable systems are also used in rehabilitation robotics [59–61]. These robots use high-bandwidth force control that allow the rendering of high stiffness and minimal friction which in turn provide a free feel to the resultant motion [111].

To ensure minimal technology disruption on the rehabilitation process, some of the technical requirements present in the design of most rehabilitation robots in the literature take into consideration the ergonomics of the system and the ability to cope with a variety of patient demographic and anthropomorphic parameters [96]. An imperative requirement in the design of the human–machine interface is that it should mimic the human therapist behaviour. That is, it should be compliant when assisting movement, provide full support within the patient's passive range of motion and nourish the patient's confidence and motivation levels through goal-oriented informative biofeedback. On the physiotherapist side, objective assessment of patient's progress can be obtained through data processing and presentation.

Rehabilitation robots for the upper limb can be grouped into two categories: End-effector and Exoskeleton-based systems (Fig. 1). For a summary of the majority of the existing upper limb rehabilitation systems available to date, please refer to Table 1 and to Table 2. End-effector systems refer to systems interacting with the patient using a single distal attachment point on the forearm by means of an orthosis (e.g. MIT-MANUS, Table 1). Exercises are defined in the XYZ Cartesian space relative to the robot's single end-effector attachment point and the assistance magnitude modulated using impedance/admittance control schemes in the robot task-space. Some End-effector systems have been developed to deliver bilateral therapies (Fig. 1) by means of a second passive or active robot single distal attachment point to the non-paretic arm (e.g. MIME and Bi-Manu-Track, Table 1).

Exoskeleton systems on the other hand encapsulate the arm on the mechanism providing the opportunity to control the orientation of the arm where the degrees of freedom are active (e.g. Armin, L-Exos, Table 2). While this means that the arm's joint axes are fully determined (allowing for larger workspace), when compared with End-effector systems, joint misalignments are possible if the Exoskeleton robot axes do not align correctly with patient's arm anatomical axes. In contrast, End-effector systems' single attachment point near the wrist results in a number of possible shoulder and elbow rotations. While it is not problematic for 2D planar systems operating over a table top (e.g. MIT-MANUS, Braccio di Ferro, Table 1), unsupported 3D spatial movements could result in joint injuries and limit the re-learning of correct arm's

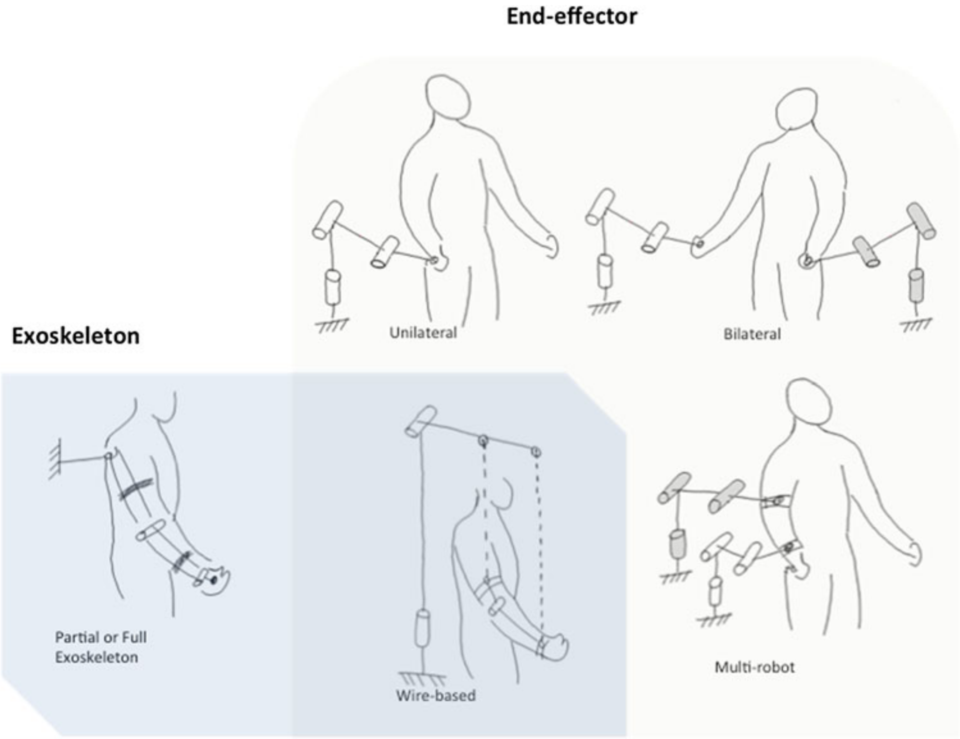

Fig. 1 Upper limb rehabilitation robot generalised mechanical categories

coordination patterns. To address this problem, some systems use a dual robot configuration (e.g. REHAROB and iPAM, Table 1) to achieve coordinated motions for the upper arm and forearm segments. Other systems employ a technique based on an overhead counter balanced mechanism (illustrated as ‘wire-based’ in Fig. 1) where wires are connected to either an exoskeleton (e.g. Dampace, Table 2) or to a splint (e.g. Swedish Helparm, Table 1) to provide passive gravity support and on active wires controlling height and orientation combined with linkages to guide the arm (e.g. NeReBot, Table 1). The Gentle/S system (Table 1) combines a single distal attachment point on the wrist with an orthosis through a passive sling suspension mechanism providing gravity support for the elbow and shoulder via a linked splint or exoskeleton (Fig. 1—Unilateral + Wire-based). The recent Gentle/G system [63] builds on Gentle/S by including a partial-exoskeleton grasp-assist robot to form a new class of multi-robot system (Fig. 1—Unilateral + Wire-based + Multi-robot + Partial Exoskeleton).

3 Upper limb robotic rehabilitation systems

Available upper limb stroke rehabilitation methodologies and technologies can be categorised as: conventional physical and occupational therapy, constraint-induced movement therapy, robotic-aided and sensor-based therapy systems. Although it could be argued that some of the passive systems summarised in Table 1 (Swedish Helparm) and Table 2 (Dampace and T-WREX) might be classed as sensor-based systems, this paper focus only on the overview of currently available robotic rehabilitation systems.

Detailed systematic technical reviews, meta-analyses, comparison of different physiotherapy schools, effects of intensity of training, and efficacy of specific upper limb rehabilitation techniques have already been published [9, 88, 89, 91, 96, 110]. Most of the robotic systems summarised in Table 1 and Table 2 are further enhanced by visual and audio feedback. It is beyond the scope of this paper to discuss all the applications for stroke rehabilitation. Readers interested in further details on virtual reality stroke applications are encouraged to consult a review article by Sveistrup [104].

3.1 Movement shaping systems

Similarly to constraint-induced movement therapy, the principle used by robotic therapies has taken advantage of the ability of robots to provide errorless repetitive movement training to address learn non-use issues. Such rehabilitation programmes are supported by the understanding that extended repetitive paretic arm movement practice will facilitate brain plasticity and cortical organisation leading to increased use of the paretic side in daily living activities.

Typically, movement shaping exercises are conceived by defining a target endpoint followed by instructions to

Table 1 End-effector-based robotic rehabilitation systems used for upper limb clinical research

System	Developer	Reference	Type	UL segment	DOF assisted	Description
Act 3D	Northwester University, USA	Sukal et al. [103]	Single-point, unilateral	Shoulder + elbow	3 active DOF, 3D space	Gravity compensated or enhanced. Passive, active assistive, resistive modes. Based on the Haptic Master robot.
ADLER	Medical College of Wisconsin, USA	Johnson et al. [45]	Single-point, bilateral	Shoulder + elbow + forearm + wrist	3 active, 3 passive DOF, 3D space	Based on the Gentle/S system. Reaching in any direction with real target objects. Used in combination with a FES glove for grasping of real objects.
ARM-Guide	Northwester University, USA	Reinkensmeyer, et al. [92]	Single-point, unilateral	Shoulder + elbow	1 active DOF, 2D space	Gravity mitigated, reaching in any plane, address learn non-use. Passive, active assistive, resistive modes. Based on slide mechanism allowing straight line movement.
Bi-Manu-Track	Klinik-Berlin/Charite Hospital Germany	Hesse et al. [38]	Multi-robot, bilateral	Forearm + wrist	1 active DOF at one time	Gravity mitigated, address learn non-use and uses mirror image movement. Passive, active assistive, resistive modes.
Braccio di Ferro	University of Genova, Italy	Casadio et al. [14]	Single-point, unilateral	Shoulder + elbow	2 active DOF, 2D space	Planar reaching. Passive, active assistive, resistive modes. Based on MIT-MANUS system.
Driver SEAT	Rehab Research Development Center at VA, Palo Alto, USA	Johnson et al. [47]	Steering wheel, bilateral	Shoulder + forearm + wrist + hand	Customised car steering wheel interface	Provides bilateral ADL movement therapy (mirror image) via instrumented steering wheel. Passive, active modes. Visual and audio feedback.
Gentle/S	University of Reading, UK	Loureiro et al. [59, 60]	Single-point + wire-based, unilateral	Shoulder + elbow + forearm + wrist	3 + 1 active, 2 passive DOF, 3D space	Gravity compensated, reaching in any direction, visual, haptic and audio feedback. Passive, active assistive, resistive, trajectory decision making. Based on Haptic Master robot.
iPAM	University of Leeds, UK	Jackson et al. [43]	Multi-robot, unilateral	Shoulder + elbow + forearm	5 active DOF, 3D space	Similarly to REHAROB system it uses two robots. Passive, active assistive modes.
MEMOS	Fondazione Salvatore Maugeri/SSSA, Italy	Colombo et al. [18]	Single-point, unilateral	Shoulder + elbow	2 active DOF, 2D space	Planar reaching. Passive, active assistive, resistive modes. Visual and audio feedback.
MIT-MANUS (InMotion2)	Massachusetts Institute of Technology/ Interactive Motion Technologies, USA	Hogan et al. [40], Krebs et al. 1998	Single-point, unilateral	Shoulder + elbow	2 active DOF, 2D space	Gravity mitigated, planar reaching, address learn non-use. Passive, active assistive, resistive modes. Based on SCARA type manipulator.
MIT-MANUS (InMotion3)		Celestino et al. [15]		Forearm + wrist	3 active DOF	Similar to above, but motion is for pro-supination of forearm and Ab-adduction, Flex-extension of wrist)

Table 1 continued

System	Developer	Reference	Type	UL segment	DOF assisted	Description
Java Therapy	University of California, Irvine, USA	Reinkensmeyer et al. [94]	Joystick, unilateral	Wrist	2 active DOF, 2D space	Limited planar motion and active assistive modes. Game-like visual and audio feedback, telerehabilitation function.
MIME	Rehab Research Development Center at VA, Palo Alto, USA	Lum et al. [71]	Single-point + digitiser bilateral	Shoulder + elbow	3 active DOF, 3D space	Mirror image passive, active assistive and resistive movement therapy. Address learn non-use, can perform also unilateral exercises.
NeReBot	University of Padova, Italy	Masiero et al. [75]	Wire-based, unilateral	Shoulder + elbow	3 active DOF, 3D space	Gravity compensated. Passive and active assistive. Visual and audio feedback. Splint, 3 wires and linkages provide arm orientation/position.
REHAROB	Budapest University of Technology and Economics, Hungary	Toth et al. [109]	Multi-robot, unilateral	Shoulder + elbow + forearm	5 active DOF, 3D space	Passive, single or multijoint coordination, range of motion training to address spasticity. Visual feedback. Based on two 6DOF industrial robots.
Swedish Helparm	Kinsman Enterprises, Inc., USA	Kinsman Enterprises [52]	Wire-based, unilateral/bilateral	Upper arm or forearm	2 passive (unilateral)	Passive sling suspension system.

the patient to reach the target. The common approach has been to encourage reach to distal touch movements with the shoulder and the elbow, except for a few hand systems (e.g. Hand Mentor, HAWARD, Rutgers Master II, Table 2) and some single degree of freedom devices targeting a specific arm joint, such as the Cozens's arm robot [20] and the recent Myomo e100 exoskeleton (Table 2) for elbow flexion/extension, and the Bi-Manu-Track device (Table 1) assisting forearm or wrist movement.

Work by Hogan and Krebs [40] on the design of the MIT-MANUS (Table 1) was the first work to evaluate the impact of robot-aided therapy [56, 112]. The MIT-MANUS robot (now commercially available as the InMotion2) is a planar SCARA type manipulator providing movement assistance on the horizontal plane. It uses force feedback to transfer forces to the end-effector handle grasped by the patient's hand to assist task completion. The MIT-MANUS is a backdriveable robot with low friction and inertia that allows the patient to exercise smooth table top movements by interacting with a computer screen showing 2D video games such as moving to targets and shape tracing. Clinical studies with over 100 stroke subjects report significant motor recovery gains at the acute [2] and chronic phases of recovery [23, 27]. Of particular interest, the results showed that subjects retained the functional gains acquired during initial robotic therapy both after 3 months [27] and at the end of 3 years following initial treatment [56, 112]. This suggests that the neuro-recovery process continued far beyond the commonly accepted 3–6 months post-stroke interval, and that neuro-recovery was dependent on the lesion location. The MIT-MANUS mechanism, however, limits the range of possible therapies, extensions for forearm and wrist assistance are available in the InMotion3 robot [15], but it is apparent that more degrees of freedom are necessary to facilitate arm movement against gravity.

Initial work at the VA Palo Alto Research and Stanford University, USA looked at the principles of symmetrical bilateral movement of the non-paretic and paretic arms [69, 70]. This work leads to the investigation of bimanual 3D motion using a distinctive approach based on the Mirror-Image Motion Enabler concept—MIME (see Table 1). MIME was the first robotic system to explore both unilateral and bilateral therapies [71]. The MIME system consists of a modified 6 DOF Puma 560 robot manipulator coupled to a force and torque transducer on a forearm splint providing support and assistance to the paretic limb, and a second splint connecting the non-paretic limb to a six DOF position digitiser. When the patient moves the non-paretic arm with the digitiser in the bilateral mode, the robot guides the paretic arm to 'mirror' the movement of the non-paretic arm. In unilateral mode, the robot can assist the paretic limb in passive, active-assisted and active-resistive modes. A controlled clinical trial comparing a chronic

Table 2 Exoskeleton based robotic rehabilitation systems used for upper limb clinical research

System	Developer	Reference	Type	UL segment	DOF assisted	Description
ARMin	ETH, Zurich, Switzerland	Nef and Riener [84]	Fixed exoskeleton, unilateral	Shoulder + elbow	4 active, 2 passive DOF	Gravity compensated, massed practice with target, visual and audio feedback, passive, active assistive.
Dampace	University of Twente, The Netherlands	Arno et al. 2007	Fixed exoskeleton, unilateral	Shoulder + elbow	5 passive DOF (3 shoulder, 2 elbow)	Gravity compensated, visual and audio feedback. Passive and resistive modes.
Hand Mentor	Kinectic Muscles, Inc. USA	Koeneman et al. [53]	Portable, partial exoskeleton, unilateral	Wrist + hand	2 active (wrist and fingers flex-extension)	Portable system, EMG and force feedback. Passive, active assisted modes. Based on McKibben pneumatic actuators.
HWARD	University of California, Irvine, USA	Takahashi et al. [105]	Fixed, partial exoskeleton, unilateral	Wrist + hand	3 active (1 wrist, 1 fingers MCP, 1 thumb)	Active assistive motion combining wrist extension with hand grasping and wrist flexion with hand release. Visual and audio feedback.
KIST	Korea Institute of Science and Technology, Korea	Kim et al. [51]	Portable, exoskeleton, bilateral	Shoulder + elbow + wrist	7 active, 6 passive DOF	Portable system, Passive, active assisted modes. Based on pneumatic and electric brake actuators.
L-EXOS (PERCRO)	Scuola Superiore Sant'Anna, Italy	Montagner et al. [78]	Fixed exoskeleton, unilateral	Shoulder + elbow	4 active, 1 passive DOF	Gravity compensated, massed practice with target, visual and audio feedback, passive, active assistive.
MGA	Georgetwon and Maryland Univ., USA	Carignan et al. [13]	Fixed exoskeleton, unilateral	Shoulder + elbow	4 active, 1 passive DOF	Gravity compensated, visual and audio feedback, passive, active assistive modes.
Myomo e100	Myomo, Inc., USA	Stein et al. [101]	Portable, partial exoskeleton, unilateral	Elbow	1 active DOF	Active assistive motion using EMG biofeedback.
Pneu-WREX	University of California, Irvine, USA	Sanchez et al. [98]	Fixed, exoskeleton, unilateral	Shoulder + elbow	4 active, 1 passive DOF	Gravity mitigated, passive, active assistive. Visual and audio feedback. Based on the T-WREX system.
RUPERT	Arizona State University, Phoenix, USA	He et al. [36]	Fixed exoskeleton, unilateral	Shoulder + elbow + wrist	4 active DOF (1 shoulder, 1 elbow, 1 forearm, 1 wrist)	Passive, active assisted. Graphical display of arm moving to goal. Based on McKibben pneumatic actuators.
Rutgers Master II	Rutgers, State University New Jersey, USA	Merians et al. [77]	Partial exoskeleton, unilateral	Hand	4 active DOF (1 thumb, 3 fingers)	Active assisted, resistive modes. Visual, haptic and audio feedback. Used custom pneumatic actuators.
T-WREX	University of California, Irvine, USA	Sanchez et al. [97]	Fixed exoskeleton, unilateral	Shoulder + elbow	5 passive DOF (3 shoulder, 2 elbow)	Gravity mitigated, passive functional task training using visual and audio feedback. Based on the Wilmington Robotic Exoskeleton.

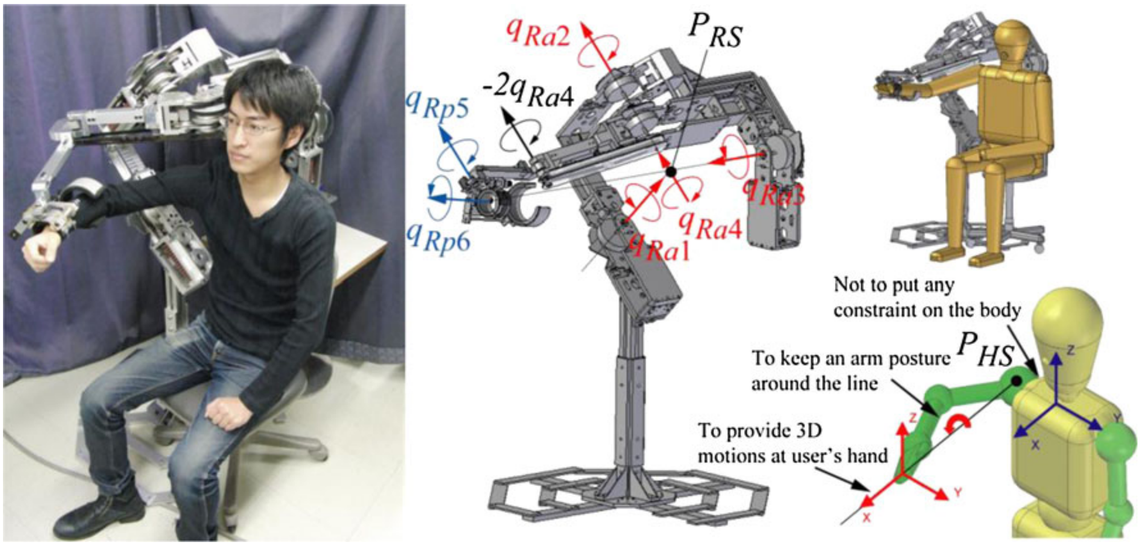

Fig. 2 Escort robotic arm. (*Left*) user interacting with the escort robot; (*right*) robot and posture configurations

stroke group using MIME therapy to an equivalent group using conventional neurodevelopment therapy showed higher Fugl-Meyer Assessment (FMA) gains for the group receiving MIME therapy [66]. A further study investigating the effectiveness of bilateral to unilateral MIME therapy used four groups at the sub-acute phase of recovery [68]. Similarly to the previous MIME study, the control group received conventional neurodevelopment therapy. The intervention group was further divided into three groups: one receiving unilateral therapy, one receiving bilateral therapy and one receiving both unilateral and bilateral therapies. In comparison, the intervention groups showed higher FMA improvements proximally than the control group, but not sustained after a 6-month follow-up. Interestingly, no significant difference was found between the group receiving unilateral only therapy and the group receiving combined unilateral and bilateral therapies. The bilateral only group results, however, showed lower gains than the other two intervention groups.

The Bi-Manu-Track system (Table 1) provides bilateral rehabilitation of the wrist flexion/extension and forearm pronation/supination, allowing passive and active-resistive movement on both limbs, and passive movement of the paretic limb to mirror the movement of the non-paretic limb [38]. Hesse and colleagues found this type of therapy to be effective in reducing spasticity and improving motor control in chronic stroke patients [38]. In another clinical study with 44 severely impaired stroke subjects at the sub-acute phase of recovery, Bi-Manu-Track bilateral therapy was compared to electrical stimulation with similar time period [39]. Subjects receiving bilateral therapy in addition to conventional therapy showed significantly higher FMA gains than the group receiving electrical stimulation in addition to conventional therapy. A difference was maintained at 3-month follow-up [39].

Following this pioneering work on bilateral movement, it is hypothesised that the ‘mirror image’ movement may facilitate functional gains by supporting corticospinal paths from the non-paretic side to the paretic side [68]. It is also suggested that the damaged hemisphere of the brain might be influenced by the undamaged hemisphere via the intercallosal fibres while the patient performs bilateral movements [37].

Johnson used the mirror image principle with the understanding that regaining the ability to drive was a strong mediator for improving patient motivation, to develop the Driver SEAT: ‘simulation environment for arm therapy’ (Table 1). The device comprises a customised design of a car steering wheel equipped with sensors to measure the forces applied by patient’s limbs, and an electrical motor to provide pre-programmed assistance and resistance torques to the wheel. Visual cues were given to the patient via a commercial available low-cost PC-based driving simulator that provided graphical road scenes. The interface allowed the participation of the patient in the task and the involvement of the paretic limb in the exercise encouraging both motor and driving relearning skills [47]. The Driver SEAT system was found to increase the interest of patients in using the impaired limb in the steering task, and the use of the automated constraint discourages compensatory use of the stronger limb [44].

The Assisted Rehabilitation and Movement Guide (ARM-Guide), a simpler and relatively inexpensive system, was developed by Reinkensmeyer et al. [92] to facilitate reaching therapy after stroke. In addition, the system has been used also to investigate various features present in stroke reaching movements [93]. The ARM-Guide (Table 1) consists of a linear track adjustable in two dimensions to allow repetitive reaching movements via a forearm splint connected to the device. Controlled clinical studies have compared ARM-Guide therapy to a controlled group practicing the same amount of time without the robot. In comparison with the results reported by the MIT-MANUS and MIME studies, the ARM-Guide results show comparable improvements between the intervention and control groups in the time to complete functional tasks and on the straightness of the reaching movements. Interestingly, the robot group showed improved trajectory smoothness when compared with the control group, perhaps due to the robot imposed smooth trajectory during robot practice [50].

The European project Gentle/S [34] extended the therapies available on the MIME system by providing movement target choice on initiation of a movement [3, 60, 61]. In common with MIME, the Gentle/S system facilitates movement therapy on the horizontal and vertical planes. It uses the three degree of freedom Haptic Master haptic interface coupled to a passive (or active) three degree of freedom gimbals mechanism to facilitate orientation of hand and assist arm movement at the wrist using a splint. Patients exercise on a table top and interact with task-oriented 3D virtual environments through visual, audio and haptic cues. To address the problem of determining the spatial position of the elbow and shoulder for 3D movements seen on the MIME unilateral therapy, the Gentle/S system combines the robot support (at the robot end-effector) with an elbow orthosis with wires suspending it from an overhead frame to support the arm against gravity. This allows for full or partial gravity adjustments depending on the subject impairment level [61]. A pilot study showed that subjects were motivated to exercise for longer periods of time when using a mixture of haptic and virtual reality systems [59]. A multicentre randomised clinical trial using an ABC-ACB crossover design evaluated the Gentle/S therapy effectiveness with chronic patients against a sling suspension intervention. The results with a cohort of 31 subjects showed increased functional gains at the end of the trial [4, 19] comparable to the MIT-MANUS [27] and MIME studies [66, 67]. Interestingly, on a recent analysis of the complete data, no significant differences were observed between the Gentle/S intervention and sling suspension intervention phase suggesting that passive gravity compensation–based therapies could have a beneficial impact on the recovery of chronic stroke patients [5, 6].

The Activities of the Daily Living Exercise Robot (ADLER) and the Arm Coordination Training (Act 3D) systems (Table 1) developed relatively recently are based on aspects of the Gentle/S system. While the Act 3D system shares the same robot platform, the ADLER system shares in addition the same gimbals and wrist splint attachment mechanism of the Gentle/S system. The Act 3D system has been used primarily to evaluate the effects of gravity on the paretic arm muscle synergies [103].

A limiting factor of the ADLER and Gentle/S systems for ADL therapies is the device's small range of motion. Exoskeletons are being used to deal with the difficulties of integrating ADL activities such that interaction with the environment while receiving force information through the robot can be more natural and achievable in a larger workspace. The ARMin system (Table 2) is the first active exoskeleton system to be developed for the shoulder, elbow and forearm providing position, force and torque sensing to facilitate patient cooperative arm therapy when movement ability to perform a task is inadequate [84]. The ARMin robot is fixed to a structure (or wall) while the patient sits underneath the structure with the arm encapsulated on a distal exoskeletal orthosis. The system combines a force reflecting exoskeleton with visual and audio cues providing game-like exercises. A pilot clinical study evaluating the efficacy of the ARMin therapy with chronic stroke patients have shown FMA gains similar to the end-effector system studies presented earlier [85].

A passive approach to using an exoskeleton has been proposed by Reinkensmeyer based on the Java Therapy concept [94]. The T-WREX system (Table 2) is a passive counter balance mechanism (now available commercially as ARMEO by HOCOMA, Switzerland) for use with low muscle strength patients. The gravity and arm mass compensation can be adjusted by adding elastic bands to the counter balance mechanism, and position and grip sensors provide movement and grip force feedback. In addition, the system provides task progress charts to the physiotherapist and exercise score information to the patient [97]. Therapy interaction is with the aid of different computer games and activities with audio feedback (e.g. shopping, cracking eggs and making lemonade). A clinical trial with chronic stroke subjects comparing T-WREX to conventional therapy showed improvements on the FMA gains comparable to the chronic studies presented previously [41, 95].

A new approach capitalising on the use of wires to design a compact portable system for use next to a bed in an acute rehabilitation ward has been proposed [75]. The NEuroREhabilitation roBOT (NeReBot) system (Table 1) consists of a three degree of freedom robot controlled by three nylon wires supporting a forearm orthosis and mounted on a wheeled frame. The system facilitates movement therapy while sitting on a chair or lying down in bed. In common to most of the rehabilitation systems summarised in Tables 1 and 2, it uses visual and audio feedback. Clinical studies with 35 acute stroke subjects [75] showed FMA gains equivalent to the MIT-MANUS acute study [2].

While exoskeleton-based systems facilitate the integration of ADL activities in a more natural and larger workspace, joint misalignments are possible if the robot axes do not align correctly with patient's arm anatomical axes, which could result in injury. A new approach has been recently proposed using an Escorting design method to minimise the effects of joint misalignments [80]. The Escort system (Fig. 2) was designed to support ADL motions while maintaining an anatomically correct posture, by supporting the user's forearm in order to move the hand in the spatial space. The system minimises potential excessive forces to the shoulder during therapy by the use of two passive joints. Existing exoskeleton systems have limited compliant motions due to their rigid design, which in turn limits natural human movement fluidness. The Escort system integrates Redundant Drive Joints (RDJs) developed for producing variable compliance at the robotic joints. The impedance control scheme for such RDJs has been proposed for producing compliant motions with higher frequencies [81], and its prototype design has been presented [42, 79]. The primary merit of this approach is that reliable compliant motions in a wide admittance range can be produced by the Escort robot joints.

3.2 Fine motor movement systems

Substantial attention has been placed on shaping therapies for the shoulder, elbow and forearm, but little work exists on fine motor control of the wrist and hand. The commercially available MIT-MANUS (InMotion3) summarised in Table 1 was developed to retrain wrist flexion–extension, abduction–adduction and pronation–supination movements. Although the authors consider its integration with the MIT-MANUS (InMotion2) shoulder and elbow robot, clinical studies have been conducted in isolation. Initial clinical results suggest that forearm and wrist therapies leads to decreased chronic stroke wrist impairment as depicted by the FMA wrist and forearm sub-score results [16]. Similar FMA improvements were reported by the developers of the MEMOS system (Table 1) with a simpler wrist flexion–extension mechanism with eight chronic stroke subjects [17].

A hand rehabilitation system based on the Rutgers Master II force feedback glove-exoskeleton (Table 2) has shown promising results with exercises designed to increase the range of motion, maximum force and velocity of the fingers and thumb [77]. The commercially available Hand Mentor system (Table 2) in contrast to the Rutgers Master II system does not retrain the fingers individually. It actively flexes and extends the wrist and fingers MCP joints in a synchronised motion and uses electrical muscle activity recordings in the control of the device to encourage muscle recruitment [53]. Based on the same wrist/fingers combined flexion–extension principle, Takahashi and colleagues developed the Hand-Wrist Assisting Robotic Device (HWARD, Table 2), a three degree of freedom pneumatically driven (and backdriveable) exoskeleton for gross real-object hand grasp [105]. It was developed on the principle that wrist extension while forming power grip activates the primary cortex and corticospinal tract. Other systems under development are looking at combining forearm pronation–supination with hand grip [57] and index finger pinch with thumb control [10]. Augmented virtual reality techniques are also being proposed to allow patients to move weightless objects while observing the virtual object and the virtual scenario overlaid with the patient's hand and an orthosis actuated by cables on the dorsal side of the hand providing assistance to finger extension [72].

3.3 Whole-arm movement systems

Although we have seen early pioneering work at the level of the hand, this has been on the form of finger training isolated from arm therapy through orthoses and exoskeleton systems [53, 77, 105]. The MIT-MANUS group has been extending their robot modules to hand rehabilitation, making their device's range able to retrain all possible upper limb joints but not all joints at the same time [55]. Their strategy is, therefore, to retrain upper limb function by breaking it down into functional components of movement. Nathan and Johnson, for example, have been developing the ADLER system to incorporate hand grasp assistance of real objects in ADL using functional electrical stimulation coupled to robot assistance to arm movement [82, 83]. The Gentle/G system was the first to integrate functional robotic reach and grasp [63] and to conduct a pilot study with acute strokes to evaluate the approach [65]. A recent study with the HENRIE rehabilitation system, providing support for pick-and-place movements, showed positive effects, suggesting that in order to maximise physical activity, consideration should be taken with the virtual task design [113] (Fig. 3).

4 Home rehabilitation robotic systems

The need to provide rehabilitation programmes beyond the hospital stay has generated substantial interest in models exploring robotics technology to deliver home rehabilitation. This is of particular importance to prevent learned non-use (LNU) in under-supervised environments outside the hospital. Learned non-use (LNU) is a common compensatory behaviour that affects most stroke survivors [107] and manifests itself as a spontaneous and preferential use of the less-impaired upper arm despite existing

Fig. 3 Whole-arm rehabilitation systems examples. (*Left*) subject exercising with the ADLER system (reprinted with permission [82]). (*Right*) subject using the Gentle/G system (reprinted with permission [64])

functional gains in the more impaired arm [102]. After discharge from inpatient rehabilitation, about 50% of stroke survivors will continue to experience upper arm disabilities and therefore must limit compensatory behaviours such as LNU in order to maintain or improve upon motor gains and neural changes resulting from inpatient therapy [32].

The challenge in delivering rehabilitation outside the clinic environment is multidimensional and often mediated by therapist availability, distance, economics (costs for long-term rehabilitation), patients' motivation and ability to be compliant with therapy prescriptions and the ability to design systems that can deliver effective therapy that will permit patients to complete prescribed therapy tasks with appropriate posture, movements and intensities [108]. From the perspective of the therapist, successful home-based rehabilitation requires oversight of patient performance and care via regular visits [29, 73, 74]. These visits can be either in person or via some form of tele-communication. The question remaining is how best to use robotic technologies to resolve the challenges to successful home rehabilitation and to meet the needs of the patients and their caregivers.

The telemedicine concept has been identified as a valid approach to extend rehabilitation robotics therapy and assessment to the home [12, 62]. Conceptual models for tele-rehabilitation service delivery have recently been proposed [24]. These are tele-consultation—video-conference technologies facilitating face-to-face but virtual interaction of therapist and patient; tele-monitoring—technologies used to monitor and assess patients; tele-therapy—therapies allowing patient play or exercise and the therapist and/or patient to change machine settings; and tele-cooperation—allowing multiple patient cooperation to complete a task or to play a game. Tele-therapy, tele-monitoring and tele-cooperation provide good opportunities for integration with robotic systems.

Tele-therapy technology in the home, however, needs to use affordable robotic systems. Achieving affordable home rehabilitation robotic systems often may mean developing systems that have lower degrees of freedom devices, incorporate simple or commercial games, and/or use passive joints, i.e., without actuation. The first robotic application of telerehabilitation is the Java Therapy system (Table 1). Java Therapy is an inexpensive robotic telerehabilitation system for unilateral forearm pronation–supination and wrist flexion–extension therapy following brain injury. It consists of a Web site with a library of evaluation and therapy activities that can be performed with a commercial force feedback joystick, which can physically assist or resist movement as the user performs therapy. An occupational therapist connected online guides the patient through a repetitive game-based regime conceived to improve arm function. Java Therapy also presents for some level of quantitative movement performance feedback, by allowing users and their caregivers to assess rehabilitation progress via the web [94]. Popescu et al. [90] used the Rutgers Master II (Table 2) with a telerehabilitation system to improve hand function of people remotely. In this system, a therapist is able to modify therapy parameters remotely while the therapy is being delivered in the patient side and off-line monitoring of patient progress.

Oftentimes, home rehabilitation system not only provides opportunities for remote therapy, but also provides feedback and through games and virtual reality tasks in order to increase patient motivation and compliance during unsupervised therapy. Bach-y-Rita and colleagues developed a home-based therapy environment by creating an environment that focused on computer-assisted motivating rehabilitation (CAMR) [7]. They developed 'Palanca', a computerised game of pong with a mechatronized handle. They showed the ability of the system to quantify impairments and with some degree of carryover gains. TheraJoy [26] focuses on home-based rehabilitation. The system used easily available low-cost joystick platform and modified it to deliver varied therapy in the horizontal and vertical planes. Johnson and colleagues have proposed Robot/Computer-Assisted Motivating Rehabilitation Suite that uses several commercial and modified low-cost joysticks and wheels such as TheraDrive [46] and the TheraJoy using a unified custom-designed software called UniTherapy [25]. Via the system, stroke patients were able to play custom or commercial tasks and games during therapy sessions. Other developments examples for tele-therapy include Colombo and colleagues' one degree of freedom wrist and 2-DOF shoulder/elbow robots packaged with simple motivational tasks and feedback metrics to increase patient intrinsic motivation and enjoyment during therapy [17] and the simulated piano that presents visual, auditory and tactile feedback to enable bilateral arm and hand therapy using cyberglove [1].

An interesting trend is the combination of passive or active robotic systems with functional-electrical stimulation (FES) [33, 54] for neurorehabilitation of the stroke or spinal cord injury impaired hand. An example of this concept is the ReJoyce commercial platform sold by HomeTelemed system that delivers Tele-therapy and Tele-monitoring via on workstation paradigm which allows the user, while wearing a 2-channel FES cuff, to assist in hand opening and closing. The robot attaches to a desktop with passive joints and via an interactive end-effector that when grasped or pressed or twisted permit the user to interact with games and complete real activities requiring reaching and grasping. Therapists are able to watch and/or guide users during the sessions. The ADLER robot therapy system is an example of use of an FES system to support grasping while the robot supports reaching movements during training on real activities of daily living involving reaching and grasping (Table 1) [83].

Tele-monitoring is becoming another essential characteristic of home rehabilitation systems. Most tele-rehabilitation systems such as JavaTherapy, ReJoyce, TheraDrive and TheraJoy via UniTherapy have methods that allow a therapist to observe a therapy session and interact with the patient users remotely and in real time. Remote monitoring can be further facilitated via wearable health-monitoring systems and activity monitors [49, 86]. More sophisticated approaches have also been evolved with the use of socially assistive robots to provide hands-off monitoring as well as assist in the delivery of therapy and motivational feedback. These autonomous assistive robots, designed to embody aspects of a therapist, are being tested in the home and hospital settings and are being accepted and tolerated by patients [31, 48, 76]. For example, Mataric and colleagues developed a novel non-contact mobile platform robotic systems capable of providing several levels of feedback and monitoring and are designed to enhance social interaction; in that, they are autonomous, engaging, and sociable [76, 99, 106]. The robot consisted of a Pioneer mobile base equipped with SICK LMS200 laser sensors and Activity Monitors along with a Sony pan-tilt-zoom (PTZ) camera for video feedback during session and a motion capture unit to wirelessly transmit movement data to the robot. The robot assisted stroke-patients by monitoring the impaired arm's activity. The robot aided the patient's rehabilitation by providing encouragements, reminders and guidance when needed. Inspired by this, Johnson and colleagues developed a low-cost mobile robot prototype called the TheraBot to integrate with TheraDrive platform to monitor posture and arm movements during remote therapy and to provide encouraging feedback during therapy [48, 100]. To achieve the lower costs, the TheraBot used a low-cost Icreate robot platform (Irobot, Inc, Boston, MA USA) as the mobile base with a X10 powered wireless camera and a low-cost speech synthesiser.

Tele-cooperation combined with tele-therapy in home rehabilitation is also feasible. Carignan and Krebs have proposed an environment based on the MIT-MANUS (In-Motion2) system to facilitate group sessions between a therapist and individual patients remotely located and interactive cooperative scenarios where the patient and therapist reach and grasp objects in a shared environment [12]. Loureiro, Johnson and Harwin go one step forward and evaluate combined tele-cooperation and tele-therapy with a patient-to-patient paradigm [64]. Their study investigated the concept of long-distance collaborative 'play' using two 6 DOF robot-mediated environments (Gentle/S and ADLER) and report on how this type of play influenced the motivation of able-bodied persons to engage, sustain play, and relate during a shared task. They conducted a randomised controlled pilot study with eighteen unimpaired subjects and reported the existence of a positive trend in favour of the collaborative robot-mediated environment, which subjects found more valuable, interesting, and enjoyable, and therefore willing to spend more time at the task. One striking observation was that some of the subjects measured initially as not interested or motivated to engage in the experiment showed increased motivation results after playing the game with an intrinsically more motivated opponent [64].

5 Assessment

There is a growing need for evidence of the effectiveness of rehabilitation robots. A universal problem is that the cost of rehabilitation robots is still high in comparison with a drug-based therapy making wide-scale evaluation problematic. Studies have been small, typically less than 50 participants, and often only a pilot evaluation to demonstrate the basic working principles of the device [8]. The high cost of evaluating rehabilitation robots in comparison with drug therapies has also limited the intensity of the intervention since it is difficult to produce multiple copies of the device to trial, as well as to provide the logistic support to ensure it is used correctly. Evidence from similar work on family therapy by Galvin et al. [30] has shown that an intervention intensity of at least 1,200 min of high-quality therapy was required over an 8-week period to show an appreciable effect. It is reasonable to assume that a similar or greater intensity is needed in the case of robot-mediated therapies. A further difference between machine-delivered therapies and drug therapies is that it is neither possible nor reasonable to evaluate the intervention with a double blinded clinical trial. Thus, although it may be possible to the metrician doing the clinical measures to be ignorant of the history, it is not possible to blind the subject to the fact they are in the intervention or the control arm of the study. Despite these difficulties, a single blinded randomised control trial on the effects on stroke recovery of rehabilitation using robot rehabilitation was begun in 2002 by the US veterans administration. Positive results were achieved despite a less than ideal realisation of therapy with a low treatment intensity (18 h) [28].

Typically, a randomised control trial will use a set of accepted clinical measures. A long-standing difficulty is that accepted clinical measures are highly subjective, take a long time to administer and may lack the sensitivity to measure a specific response of interest. It is still early in the evaluation of the technology and although as yet the main driver for uptake of machine delivered therapies will probably be one of reduction of the overall cost of treatment, there are still opportunities for demonstrating the benefits that can only be delivered by robotic devices. One of these benefits is likely to be the ability to determine implicit metrics of recovery. It may well be possible to embed these in the machine delivering the therapy and as a result reduce the time needed for the clinical professional to obtain the information. A key benefit is also that metrics performed by a robot will be more objective, but that is countered by a concern over the sensitivity, as well as the ability to measure over several dimensions of interest such as spasticity, reflexes, level of voluntary control, and functional movements.

Although collecting position, velocities, accelerations and forces from the robot arm is not usually problematic, the challenge is processing of this data into metrics that correlate with accepted clinical measures. Techniques used to assess motor learning in neuroscience have been used both as a driver for rehabilitation and as an assessment tool. Patton et al. [87] investigated the classic ‘curl fields’ whereby a perturbation force is applied perpendicular to the line of movement proportional to velocity. They found that an error magnification technique could be used to enhance short-term learning, but there was no correlation with the clinical Fugl-Meyer scores used as an indicator of functional impairment.

Combining the ability to deliver treatments as well as assess results is possibly unique to technology-based interventions such as rehabilitation robotics. The specific difficulty is to determine a set of force or position perturbations that can be explicitly or implicitly applied that can then be used to either diagnose the problems in the underlying neuro-muscular structure, or be related to established clinical measures.

6 Discussion

The most comprehensive clinical trial to date regarding the effectiveness of robot-assisted therapy was published in 2010 in the New England Journal of Medicine by Lo and colleagues indicate mixed evidence for the utility of robot-assisted therapy for upper arm rehabilitation after stroke [58]. The main conclusions indicate that after 36, 1-h, high-intensity therapy with the In motion robot (MIT-Manus paradigm with horizontal, vertical, wrist and hand modules), moderate to severe functioning stroke survivors with upper limb impairment for at least 6 month and with lesions due to single and multiple strokes did not improve significantly more than non-robot control groups of usual care or intensive therapy but had a modest improvements over 36 weeks. The cost of robot therapy was comparable to the non-robot therapies (12 weeks: $9,977 RT vs. $8,269 non-RT and 36 weeks: $15,562 RT vs. $15,605 and $14,343 for non-RT). Despite these mixed results, robot-assisted therapies should still be pursued [21]. The use of the robot as an assessment tool during therapy along with the ability to provide more sensitive measures of motor change is significant and provides a feature not typical in non-robot therapies. In addition, these systems provide a test bed for evaluating other paradigms for therapy and the impact of therapy on brain repair. Another important fact supporting the continued pursuit and development of robot-assisted systems/therapies is that as cost decreases and their ability to deliver autonomous therapy in the home therapy via the use of tele-therapy, tele-monitoring and tele-cooperation paradigms improves, the cost-to-benefit ratio will improve and may tip the scale in their favour.

Commercialisation and technology transfer efforts should be pursued and are the key to improving robot-therapy systems. On-going commercial efforts persist on two fronts, (1) the development of whole arm systems and (2) the development of more affordable home rehabilitation systems. Some key players in the whole arm rehabilitation robotic device development for therapeutic applications are Hocoma[1] and Interactive Motion Technologies[2] (IMT). For example, Hocoma has made the T-WREX robot into the ARMEO and the ARMin into ARMEO Power, while IMT has made the MIT-MANUS into the Inmotion Arm and Hand Robots. These systems are involved in clinical trials. Examples of companies in home rehabilitation device development for the upper limb include small start-ups such as Myomo,[3] which developed an active exo-skeletal FES orthosis system and HomeTelemed,[4] which commercialised the ReJoyce system.

Despite mounting evidence suggesting robot-mediated therapies are not more likely to improve patients' activities of the daily living than any other therapy, such technologies have shown great capacity to improve participants' paretic limb motor function and core strength. One obstacle still present on the acceptance of this type of technology in clinical practice relates to the clinical evidence thus far generated. Varied clinical outcomes—which could be attributed to variations on patient characteristics, therapy exposure and intensity—prompt for careful interpretation of the data and for guidelines on study design and assessment to be established by the researchers and clinicians working in the field. Perhaps, it is as important as pushing for more efficient, safer and affordable technology.

7 Conclusion

One significant aspect of robot-mediated therapy devices, when compared with conventional therapy paradigms, is the increase in possible repetitions during arm and hand training and movement practice without active assistance from a therapist, which has shown to improve morale and motivation, and promote increased training at the patient's convenience in environments such as the home. There is now an opportunity, and a challenge, to integrate robot-mediated therapy principles in a social context allowing patients to interact with fellow patients or family members. In trying to deploy such technologies in under-supervised environments, safety and social inclusion issues arises the need to monitor the patient's movements as well as their internal states such that devices can predict and adapt to the user's needs. Incorporating psychophysiological sensory information to arousal and monitoring of patients' brain activities present exciting possibilities for the next generation of robot-mediated therapy devices.

References

1. Adamnovich SV, Fluet GG, Mathai A et al (2009) Design of a complex virtual reality simulation to train finger motion for persons with hemiparesis: a feasibility study. J Neuroeng Rehabil 6:28. doi:10.1186/1743-0003-6-28
2. Aisen ML, Krebs HI, Hogan N, McDowell F, Volpe BT (1997) The effect of robot-assisted therapy and rehabilitative training on motor recovery following a stroke. Arch Neurol 54:443–446
3. Amirabdollahian F, Loureiro R, Harwin W (2002) Minimum jerk trajectory control for rehabilitation and haptic applications. In: Proceedings of IEEE international conference on robotics and automation (ICRA 2002), May 2002, Washington DC, USA, IEEE, pp 3380–3385
4. Amirabdollahian F, Gradwell E, Loureiro R, Collin C, Harwin W (2003) Effects of the gentle/s robot mediated therapy on the outcome of upper limb rehabilitation post-stroke: analysis of the battle hospital data. In: Proceedings of 8th international conference on rehabilitation robotics (ICORR 2003), KAIST, Republic of Korea, pp 55–58
5. Amirabdollahian F, Harwin WS, Loureiro RCV (2007b). Analysis of the fugl-meyer outcome measures assessing the effectiveness of robot-mediated stroke therapy. In: Proceedings of IEEE 10th international conference on rehabilitation robotics (ICORR 2007), 12–14 June, Noordwijk, The Netherlands, pp 729–735
6. Amirabdollahian F, Loureiro RCV, Collin C, Harwin WS, Johnson G (2007) Analysis of the fugl-meyer measures assessing the effectiveness of the GENTLE/s rehabilitation robotics system delivering upper limb therapies. In special issue on rehabilitation robotics. J Neuroeng Rehabil 4:4
7. Bach-y-Rita P, Wood S, Leder R, Paredes O, Bahr D, Bach-y-Rita EW (2002) Computer assisted motivating rehabilitation for institutional, home, and educational late stroke programs. Top Stroke Rehabil 8(4):1–10
8. Balasubramanian S, Klein J, Burdet E (2010) Robot-assisted rehabilitation of hand function. Curr Opin Neurol 23(6):661–670
9. Barreca S, Wolf S, Fasoli S, Bohannon R (2003) Treatment interventions for the paretic upper limb of stroke survivors: a critical review. Neurorehabil Neural Repair 17(4):220–226
10. Brewer BR, Klatzky R, Matsuoka Y (2006) Initial therapeutic results of visual feedback manipulation in robotic rehabilitation. International workshop on virtual rehabilitation, pp 160–166
11. Broeks JG, Lankhorst GJ, Rumping K, Prevo AJ (1999) The long-term outcome of arm function after stroke: results of a follow up study. Disabil Rehabil 21(8):357–364
12. Carignan C, Krebs HI (2006) Telerehabilitation robotics: bright lights, big future? J Rehabil Res Dev 43(5):695–710
13. Carignan C, Tang J, Roderick S, Naylor M (2007) A configuration-space approach to controlling a rehabilitation arm exoskeleton. In: Proceedings of the 2007 IEEE 10th international conference on rehabilitation robotics, 12–15 June, Noordwijk, The Netherlands, pp 179–187
14. Casadio M, Sanguineti V, Morasso PG, Arrichiello V (2006) Braccio di Ferro: a new haptic workstation for neuromotor rehabilitation. Technol Health Care 14(3):123–142
15. Celestino J, Krebs HI, Hogan N (2003) A robot for wrist rehabilitation: characterization and initial results. In: Proceedings of the 8th international conference on rehabilitation robotics, Daejon, South Korea
16. Charles SK, Krebs HI, Volpe B, Lynch D, Hogan N (2005) Wrist rehabilitation following a stroke: initial clinical results. In: Proceedings of the IEEE 9th international conference on rehabilitation robotics, Chicago, IL, USA, pp 13–16
17. Colombo R, Pisano F, Mazzone A, Delconte C, Micera S, Carrozza MC, Dario P, Minuco G (2007) Design strategies to

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[1] http://www.hocoma.com.

[2] http://interactive-motion.com.

[3] http://www.myomo.com.

[4] http://www.hometelemed.com.

improve patient motivation during robot-aided rehabilitation. J Neuroeng Rehabil 4:3. doi:10.1186/1743-0003-4-3

18. Colombo R, Pisano F, Micera S, Mazzone A, Delconte C, Carrozza MC, Dario P, Minuco G (2005) Robotic techniques for upper limb evaluation and rehabilitation of stroke patients. In: Proceedings of IEEE 9th international conference on rehabilitation robotics, June 28–July 1, Chicago, IL, USA, pp 515–518
19. Coote S, Stokes E, Murphy B, Harwin W (2003) The effect of GENTLE/S robot-mediated therapy on upper extremity dysfunction post stroke, In: Proceedings of 8th international conference on rehabilitation robotics (ICORR 2003), KAIST, Republic of Korea, pp 59–61
20. Cozens JA (1999) Robotic assistance of an active upper limb exercise in neurologically impaired patients. IEEE Trans Rehabil Eng 7(2):254–256
21. Cramer SC (2010) Brain repair after stroke. N Engl J Med. doi: 10.1056/NEJMe1003399. 16 April, pp 1–3
22. Dijkers MP, deBear PC, Erlandson RF, Kristy K, Geer DM, Nichols A (1991) Patient and staff acceptance of robot technology in occupational therapy: a pilot study. J Rehabil Res Dev 28(2):33–44
23. Fasoli SE, Krebs HI, Stein J, Frontera WR, Hughes R, Hogan N (2004) Robotic therapy for chronic motor impairments after stroke: follow-up results. Arch Phys Med Rehabil 85(7):1106–1111 [PMID: 15241758]
24. Feng X, Winters JM (2006) Emerging personalized home rehabilitation: integrating service with interface, in medical instrumentation: accessibility and usability considerations. In: Winters JM and Story MF (eds) Chapter 27, CRC Press, Boca Raton, FL, pp 355–372
25. Feng X, Winters JM (2007) An interactive framework for personalized computer-assisted neurorehabilitation. IEEE Trans Inf Technol Biomed 518–526
26. Feng X, Ellsworth C, Johnson L, Winters JM (2004) UniTherapy: software design and hardware tools of teletherapy. RESNA, Orlando
27. Ferraro M, Palazzolo JJ, Krol J, Krebs HI, Hogan N, Volpe BT (2003) Robot-aided sensorimotor arm training improves outcome in patients with chronic stroke. Neurology 61:1604–1607
28. Finley MA, Fasoli SE, Dipietro L, Ohlhoff J, MacClellan L, Meister C, Whitall J, Macko R, Bever CT, Krebs HI, Hogan N (2005) Short-duration robotic therapy in stroke patients with severe upper-limb motor impairment. J Rehabil Res Dev 42(5):683–691
29. Fisher BE, Sullivan KJ (2001) Activity-dependent factors affecting poststroke functional outcomes. Top Stroke Rehabil 8(3):31–44
30. Galvin R, Murphy B, Cusack T, Stokes E (2008) The impact of increased duration of exercise therapy on functional recovery following stroke—what is the evidence? Top Stroke Rehabil 15(4):365–377
31. Gockley R, Mataric MJ (2006) Encouraging physical therapy compliance with a hands-off mobile robot. HRI 150–155
32. Gresham GE, Duncan PW, Stason WB, Adams HP, Adelman AM, Alexander DN, Bishop DS, Diller L, Donaldson NE, Granger CV, Holland AL, Kelly-Hayes M, McDowell FH, Myers L, Phipps MA, Roth EJ, Siebens HC, Tarvin GA, Trombly CA (1995) Post-stroke rehabilitation. Clinical practice guideline. US Department of Health and Human Services, Public Health Service, Agency for Health Care Policy and Research
33. Gritsenko V, Prochazka A (2004) A functional electric stimulation-assisted exercise therapy system for hemiplegic hand function. Arch Phys Med Rehabil 85:881–885
34. Harwin W, Loureiro R, Amirabdollahian F, Taylor M, Johnson G, Stokes E, Coote S, Topping M, Collin C, Tamparis S, Kontoulis J, Munih M, Hawkins P, Driessen B (2001) The GENTLES/S project: a new method of delivering neuro-rehabilitation. In: Marincek Crt, Buhler C, Knops H, Andrich R (eds) proceedings association for the advancement of assistive technology in Europe (AAATE 2001), Assistive technology—added value to the quality of life, assistive technology research series, vol 10. IOS Press, pp 36–41
35. Harwin WS, Patton JL, Edgerton VR (2006) Challenges and opportunities for robot-mediated neurorehabilitation. Proc IEEE 94(9):1717–1726
36. He J, Koeneman EJ, Schultz RS, Huang H, Wanberg J, Herring DE, Sugar T, Herman R, Koeneman JB (2005) Design of a robotic upper extremity repetitive therapy device. In: Proceedings of the 9th IEEE international conference on rehabilitation robotics, June 28–July 1, Chicago, USA, pp 95–98
37. Hesse S, Schmidt H, Werner C (2006) Machines to support motor rehabilitation after stroke: 10 years of experience in Berlin. J Rehabil Res Dev 43(5):671–678
38. Hesse S, Schulte-Tigges G, Konrad M, Bardeleben A, Werner C (2003) Robot-assisted arm trainer for the passive and active practice of bilateral forearm and wrist movements in hemiparetic subjects. Arch Phys Med Rehabil 84(6):915–920
39. Hesse S, Werner C, Pohl M, Rueckriem S, Mehrholz J, Lingnau ML (2005) Computerized arm training improves the motor control of the severely affected arm after stroke: a single-blinded randomized trial in two centers. Stroke 36(9):1960–1966
40. Hogan N, Krebs HI, Charnnarong J, Srikrishna P, Sharon A (1992) MIT-MANUS: a workstation for manual therapy and training. IEEE international workshop on robot and human communication, pp 161–165
41. Housman SJ, Le V, Rahman T, Sanchez RJ, Reinkensmeyer DJ (2007) Arm-training with T-WREX after chronic stroke: preliminary results of a randomized controlled trial. In: Proceedings of the 2007 IEEE 10th international conference on rehabilitation robotics, 12–15 June, Noordwijk, The Netherlands, pp 562–568
42. Ikegami Y, Nagai K, Loureiro RCV, Harwin WS (2009) “Design of redundant drive joint with adjustable stiffness and damping mechanism to improve joint admittance”. In: Proceedings of international conference on rehabilitation robotics 2009 (ICORR 2009), pp 202–210
43. Jackson AE, Holt RJ, Culmer PR, Makower SG, Levesley MC, Richardson RC, Cozens JA, Williams MM, Bhakta BB (2007) Dual robot system for upper limb rehabilitation after stroke: the design process. Proc IMechE Part C: J. Mech Eng Sci 1–13
44. Johnson MJ, Van der Loos HFM, Burgar CG, Shor P, Leifer LJ (2001) Designing a robotic therapy device to motivate use of the impaired limb. In: Mounir Mokhtari (ed) Integration of assistive technology in the information age, vol 9. IOS Press, pp 123–132
45. Johnson MJ, Wisneski HJ, Anderson J, Nathan D, Smith R (2006) Development of ADLER: the activities of the daily living exercise robot. IEEE-EMBS Biomedical Robotics (BioRob 2006), February 2006. Pisa, Italy, pp 881–886
46. Johnson MJ, Feng X, Johnson LM, Winters J (2007) Potential of a suite of robot/computer-assisted motivating systems for personalized, home-based, stroke rehabilitation. Neuroeng Rehabil 4:6
47. Johnson MJ, Van der Loos HFM, Burgar CG, Leifer LJ (1999) Driver’s SEAT: simulation environment for arm therapy. In: International conference on rehabilitation robotics (ICORR 1999), Stanford, CA, USA, pp 227–234
48. Johnson MJ, Shakya Y, Strachota E, Ahamed SI (2011) Low-cost monitoring of patients during unsupervised robot/computer assisted motivating stroke rehabilitation. Biomed Tech 56:5–9. doi:10.1515/BMT.2010.050
49. Jovanov E, Milenkovic A, Otto C, Groen PC (2005) A wireless body area network of intelligent motion sensors for computer assisted physical rehabilitation. J Neuroeng Rehabil 2:6

50. Kahn LE, Zygman ML, Rymer WZ, Reinkensmeyer DJ (2001) Effect of robot-assisted reaching and unassisted exercise on functional reaching in chronic hemiparesis. In: Proceedings of the 23rd annual international conference of the IEEE engineering in medicine and biology society, Instanbul, Turkey, pp 1344–1347
51. Kim YS, Lee J, Lee S, Kim M (2005) A force reflected exoskeleton-type masterarm for human–robot interaction. IEEE Trans Syst Man Cybern A, Syst Humans 35(2):198–212
52. Kinsman Enterprises (2007) Product catalog, pp 11. Available at: http://www.kinsmanenterprises.com/
53. Koeneman EJ, Schultz RS, Wolf SL, Herring DE, Koeneman JB (2004) A pneumatic muscle hand therapy device. In: Proceedings of the 26th annual international conference of the IEEE EMBS, 1–5 September, San Francisco, CA, USA, pp 2711–2713
54. Kowalczewski J, Gritsenko V, Ashworth N, Ellaway P, Prochazka A (2007) Upper-extremity functional electric stimulation-assisted exercises on a workstation in the subacute phase of stroke recovery. Arch Phys Med Rehabil 88:833–839
55. Krebs HI (2007) Robot-mediated movement therapy: a tool for training and evaluation. European symposium technical aids for rehabilitation, TAR 2007, 25–26 January, Berlin, Germany
56. Krebs HI, Hogan N, Volpe BT, Aisen ML, Edelstein L, Diels C (1999) Robot-aided neuro- rehabilitation in stroke: three-year follow-up. In: International conference on rehabilitation robotics (ICORR 1999), Stanford, CA, USA, pp 34–41
57. Lambercy O, Dovat L, Johnson V, Salman B, Wong S, Gassert R, Milner T, Leong TC, Burdet E (2007). Development of a robot-assisted rehabilitation therapy to train hand function for activities of daily living. In: Proceedings of IEEE 10th international conference on rehabilitation robotics (ICORR 2007), 12–14 June, Noordwijk, The Netherlands, pp 678–82
58. Lo A, Guarino P et al. (2010) Robot-assisted therapy for long-term upper-limb impairment after stroke. N Engl J Med 1–13. 16 April, doi:10.1056/nejmoa0911341
59. Loureiro R, Amirabdollahian F, Coote S, Stokes E, Harwin W (2001a). Using haptics technology to deliver motivational therapies in stroke patients: concepts and initial pilot studies. In: Proceedings of the 1st European conference on haptics (Euro-Haptics 2001), educational technology research paper series, University of Birmingham, Birmingham, UK, pp 1–6, ISSN 1463-9394
60. Loureiro R, Amirabdollahian F, Driessen B, Harwin W (2001). A novel method for computing natural path for robot assisted movements in synthetic worlds. In: Marincek Crt, Buhler C, Knops H, Andrich R (eds) proceedings association for the advancement of assistive technology in Europe (AAATE 2001), Assistive technology—added value to the quality of life, Assistive technology research series, vol 10. IOS Press, pp 262–267
61. Loureiro R, Amirabdollahian F, Topping M, Driessen B, Harwin W (2003) Upper limb mediated stroke therapy—GENTLE/s approach. In special issue on rehabilitation robotics, J Autono Robots, Springer, 15(1):35–51, ISSN: 0929-5593
62. Loureiro RCV, Harwin WS, Collin CF, Johnson M (2005) Technology driven therapy for stroke rehabilitation: beyond hospital treatment. Int J Dis Human Dev 4(3):169–175
63. Loureiro RCV, Harwin WS (2007) Reach and grasp therapy: design and control of a 9-DOF robotic neuro-rehabilitation system. In: Proceedings of the IEEE 10th international conference on rehabilitation robotics, 12–15 June, Noordwijk, The Netherlands, pp 757–762
64. Loureiro RCV, Johnson M, Harwin WS (2006) Collaborative tele-rehabilitation: a strategy for increasing engagement. In: Proceedings of the first IEEE/RAS-EMBS international conference on biomedical robotics and biomechatronics. 20–22 February, Pisa, Italy
65. Loureiro RCV, Lamperd B, Collin C, Harwin WS (2009) Reach and grasp therapy: effects of the Gentle/G system assessing subacute stroke whole-arm rehabilitation. In: Proceedings of IEEE 11th international conference on rehabilitation robotics (ICORR 2009), 23–26 June, Kyoto, Japan, pp 755–760
66. Lum PS, Burgar CG, Kenney DE, Van der Loos MHF (2002) Quantification of force abnormalities during passive and active-assisted upper-limb reaching movements in post-stroke hemiparesis. IEEE Trans Biomed Eng 46(6):652–662
67. Lum PS, Burgar CG, Shor PC, Majmundar M, Van der Loos M (2002) Robot-assisted movement training compared with conventional therapy techniques for the rehabilitation of upper-limb motor function after stroke. Arch Phys Med Rehabil 83(7):952–957
68. Lum PS, Burgar CG, Van der Loos M, Shor PC, Majmundar M, Yap R (2006) MIME robotic device for upper-limb neurorehabilitation in subacute stroke subjects: a follow-up study. J Rehabil Res Dev 43(5):631–642
69. Lum PS, Lehman SL, Reinkensmeyer DJ (1995) The bimanual lifting rehabilitator: an adaptive machine for therapy of stroke patients. IEEE Trans Rehab Eng 3:166–174
70. Lum PS, Reinkensmeyer DJ, Lehman SL (1993) Robotic assist devices for bimanual physical therapy: preliminary experiments. IEEE Trans Rehab Eng 1:185–191
71. Lum PS, Van der Loos M, Shor P, Burgar CG (1999) A robotic system for upper limb exercises to promote recovery of motor function following stroke. In: International conference on rehabilitation robotics (ICORR 1999), Stanford, CA, USA, pp 235–239
72. Luo X, Kenyon RV, Kline T, Waldinger HC, Kamper DG (2005) An augmented reality training environment for post-stroke finger extension rehabilitation. Proceedings of the 9th IEEE international conference on rehabilitation robotics, June 28–July 1, Chicago, IL, USA, pp 329–32
73. Maclean N, Pound P (2000) A critical review of the concept of patient motivation in the literature on physical rehabilitation. Soc Sci Med 50(4):495–506
74. Maclean N, Pound P, Wolfe C, Rudd A (2000) Qualitative analysis of stroke patients' motivation for rehabilitation. Br Med J 321:1051–1054
75. Masiero S, Celia A, Rosati G, Armani M (2007) Robotic-assisted rehabilitation of the upper limb after acute stroke. Arch Phys Med Rehabil 88:142–147
76. Mataric MJ, Eriksson J, Fiel-Seifer DJ, Winstein CJ (2007) Socially assistive robotics for post-stroke rehabilitation. J Neuroeng Rehabil 4:5
77. Merians A, Poizner H, Boian R, Burdea G, Adamovich S (2006) Sensorymotor training in a virtual environment: does it improve functional recovery post-stroke? Neurorehabil Neural Repair 20(2):252–267
78. Montagner A, Frisoli A, Borelli L, Procopio C, Bergamasco M, Carboncini MC, Rossi B (2007) A pilot clinical study on robotic assisted rehabilitation in VR with an arm exoskeleton.In: Proceedings of IEEE virtual rehabilitation, 27–29 September, Venice, pp 57–64
79. Nagai K, Dake Y, Shiigi Y, Loureiro RCV, Harwin WS (2010) Design of redundant drive joints with double actuation using springs in the second actuator to avoid excessive active torques. In: Proceedings of international conference on robotics and automation 2010 (ICRA 2010), pp 805–812
80. Nagai K, Kojima Y, Yonemoto S, Okubo T, Loureiro RCV, Harwin WS (2007) Structural design of an escort type rehabilitation robot for post-stroke therapies of upper-limb. In: Proceedings of international conference on rehabilitation robotics 2007 (ICORR 2007), pp 1121–1128
81. Nagai K, Shiigi Y, Ikegami Y, Loureiro RCV, Harwin WS (2009). Impedance control of redundant drive joints with double

actuation. In: Proceedings of international conference on robotics and automation 2009 (ICRA 2009), pp 1528–1534

82. Nathan D, Johnson MJ (2008) Feasibility of integrating FES grasp assistance with a task-oriented robot-assisted therapy environment: a case study. In: Second annual international conference on biomedical robotics (BioRob 2008), October 2008, Scottsdale, AZ
83. Nathan DE, Johnson MJ, McGuire JM (2009) Design and validation of a low-cost assistive glove for assessment and therapy of the hand during ADL-focused robotic stroke therapy. J Rehabil Res Dev 46(5):587–602
84. Nef T, Riener R (2005). ARMin—design of a novel arm rehabilitation robot. In: 9th IEEE conference on rehabilitation robotics, Chicago, USA, pp 57–60
85. Nef T, Mihelj M, Kiefer G, Pemdl C, Muller R, Riener R (2007) ARMin—exoskeleton arm therapy in stroke patients. In: Proceedings of the 10th IEEE conference on rehabilitation robotics, Noordwijk, The Netherlands, pp 68–74
86. Otto C, Milenkovic A, Sanders C, Jovanov E (2006) System architecture of a wireless body sensor network for ubiquitous health monitoring. J Mobile Multimed 1(4):307–326
87. Patton JL, Stoykov ME, Kovic M, Mussa-Ivaldi FA (2006) Evaluation of robotic training forces that either enhance or reduce error in chronic hemiparetic stroke survivors. Exp Brain Res 168(3):368–383
88. Platz T (2003) Evidence-based arm rehabilitation—a systematic review of the literature. Nervenartz 74(10):841–849
89. Mehrholz J, Platz T, Kugler J, Pohl M (2008) Electromechanical and robot-assisted arm training for improving arm function and activities of daily living after stroke. Cochrane database of systematic reviews, Issue 4. Art. no.: CD006876. doi:10.1002/14651858.CD006876.pub2
90. Popescu VG, Burdea GC, Bouzit M, Hentz VR (2000) A virtual-reality-based telerehabilitation system with force feedback. IEEE Trans Inf Technol Biomed 3(1):45–51
91. Prange G, Jannink M, Groothuis-Oudshoorn C, Hermens H, IJzerman M (2006) Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke. J Rehabil Res Dev 43(2):171–184
92. Reinkensmeyer DJ, Dewald JP, Rymer WZ (1999) Guidance-based quantification of arm impairment following brain injury: a pilot study. IEEE Trans Rehabil Eng 7(1):1–11
93. Reinkensmeyer DJ, Kahn LE, Averbuch M, McKenna-Cole A, Schmit BD, Rymer WZ (2000) Understanding and treating arm movement impairment after chronic brain injury: progress with the ARM guide. J Rehabil Res Dev 37:653–662
94. Reinkensmeyer DJ, Pang CT, Nessler JA, Painter CC (2001) Java therapy: web-based robotic rehabilitation. In: Mounir Mokhtari (ed) Integration of assistive technology in the information age, vol 9. IOS Press, pp 66–71
95. Reinkensmeyer DJ, Housman SJ (2007) If I can't do it once, why do it a hundred times?: Connecting volition to movement success in a virtual environment motivates people to exercise the arm after stroke". IEEE virtual rehabilitation, 27–29 September, Venice, Italy, pp 44–48
96. Riener R (2007) Robot-aided rehabilitation of neural function in the upper extremities. Acta Neurochir Suppl 97(1):465–471
97. Sanchez R, Reinkensmeyer D, Shah P, Liu J, Rao S, Smith R, Cramer S, Rahman T, Bobrow J (2004) Monitoring functional arm movement for home-based therapy after stroke. IEEE Eng Med Biol Soc Meeting, San Francisco, CA, September 1–5:4787–4790
98. Sanchez R, Wolbrecht R, Smith R, Liu J, Rao S, Cramer S, Rahman T, Bobrow J, Reinkensmeyer D (2005) A pneumatic robot for re-training arm movement after stroke: rationale and mechanical design. In: 9th IEEE conference on rehabilitation robotics, June 28–July 1, Chicago, USA, pp 500–504
99. Seifer DF, Skinner K, Mataric MJ (2007) Benchmarks for evaluating socially assistive robotics, interaction studies: psychological benchmarks of human-robot interaction. 8:3, 423–439
100. Shakya Y, Johnson MJ (2008) A mobile robot therapist for under-supervised training with robot/computer assisted motivating systems. IEEE EMBS international conference, pp 4511–4514
101. Stein J, Narendran K, Mcbean J, Krebs K, Hughes R (2007) Electromyography-controlled exoskeletal upper-limb-powered orthosis for exercise training after stroke. Am J Phys Med Rehabil 86:255–261
102. Sterr A, Freivogel S, Schmalohr D (2002) Neurobehavioral aspects of recovery: assessment of the learned non-use phenomenon in hemiparetic adolescents. Arch Phys Med Rehabil 83(12):1726–1731
103. Sukal TM, Ellis MD, Dewald JPA (2005). Dynamic characterization of upper limb discoordination following hemiparetic stroke. In: 9th IEEE international conference on rehabilitation robotics, Chicago, USA, pp 519–521
104. Sveistrup H (2004). Motor rehabilitation using virtual reality. J NeuroEng Rehabil 1(10)
105. Takahashi CD, Der-Yeghiaian L, Le VH, Cramer SC (2005) A robotic device for hand motor therapy after stroke. In: Proceedings of the 9th IEEE international conference on rehabilitation robotics, June 28–July 1, Chicago, IL, USA, pp 17–20
106. Tapus A, Mataric MJ (2006) Towards socially assistive robotics. Int J Robotics Soc 24:5
107. Taub E, Wolf SL (1997) Constraint induced movement techniques to facilitate upper extremity use in stroke patients. Topics Stroke Rehabil 3:38–61
108. Timmermans A, Seelen H, Willmann RD, Kingma H (2009) Technology-assisted training of arm-hand skills in stroke: concepts on reacquisition of motor control and therapist guidelines for rehabilitation technology design. J NeuroEng Rehabil 6:1. doi:10.1186/1743-0003-6-1
109. Toth A, Arz G, Fazekas G, Bratanov D, Zlatov N (2004) Post stroke shoulder-elbow physiotherapy with industrial robots. In: Zenn Bien Z, Dimitar Stefanov (eds) Advances in rehabilitation robotics, human-friendly technologies on movement assistance and restoration for people with disabilities. LNCIS series, Springer Verlag, Berlin, Germany, pp 391–411, ISBN: 3-540-21986-2
110. Van der Lee J, Snels I, Beckerman H, Lankhorst G, Wagenaar R, Bouter L (2001) Exercise therapy for arm function in stroke patients: a systematic review of randomized controlled trials. Clin Rehabil 15(1):20–31
111. Van der Linde RQ, Lammertse P, Frederikson E, Ruiter B (2002) The haptic master, a new high- performance haptic interface. EUROHAPTICS 2002, Edinburgh
112. Volpe BT, Krebs HI, Hogan N, Edelstein L, Diels CM, Aisen ML (1999) Robot training enhanced motor outcome in patients with stroke maintained over 3 years. Neurology 53(8):1874–1876
113. Ziherl J, Novak D, Olen!ek A, Mihelj M, Munih M (2010) Evaluation of upper extremity robot-assistances in subacute and chronic stroke subjects. J Neuroeng Rehabil 7:1–9