Rehabilitation robots: a compliment to virtual reality

J.V.G. Robertson[1, 2], N. Jarrassé[3], A. Roby-Brami[1, 2, 4]

[1]Laboratoire Neurophysique et physiologie, Université Paris Descartes, CNRS UMR 8119. 45 rue des Saints Pères, Paris 75006.
[2]Service MPR, Hôpital Raymond Poincaré, 92380 Garches.
[3]Institut Systèmes Intelligents et Robotique, Université Pierre et Marie Curie, CNRS UMR 7222, 4 place Jussieu, 75252 Paris Cedex 05.
[4]Institut fédératif de recherche sur le Handicap (IFR25).

The aim of this paper is to discuss the use of robots for upper limb rehabilitation following strokes in adults. We describe the main robots currently being developed and the results of clinical studies that have been carried out. The association of virtual reality interfaces and the robotic rehabilitation programs providing therapy in the form of games with a view to helping therapists increase the duration of rehabilitation exercise.

Le but de cet article est de discuter l'apport de la robotique pour la rééducation du membre supérieur à la suite d'un accident vasculaire cérébral chez les adultes. Les principaux robots qui ont été développés sont décrits en relation avec les résultats des évaluations cliniques. Le couplage entre des interfaces de réalité virtuelle et les programmes de rééducation utilisant les robots offre des ouvertures thérapeutiques sous forme de jeux en vue d'aider les thérapeutes à accroître la durée des exercices de rééducation.

Introduction

Over the past fifteen years, a plethora of rehabilitation robots in many shapes and forms have popped out from laboratories all over the world. Many have not yet got beyond the stage of feasibility tests. However, a few have begun to be evaluated in clinical trials and today we are beginning to have an idea of the effects of robotic therapy on recovery of motor function, even though many questions remain unanswered. Robots have been developed to compensate for loss of motor capacity [ROB 02], for retraining gait [HES 06, MAY 07]

J.V.G. Robertson, N. Jarrassé, A. Roby-Brami
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and for upper limb rehabilitation. Robots are highly complementary to virtual reality for therapy as they can provide a haptic interface and/or support and assistance. The aim of this paper is to discuss the use of robots for upper limb rehabilitation following stroke in adults. Firstly we will describe the main robots currently being developed and the results of clinical studies which have been carried out. We will then go on to discuss the perspectives for this type of rehabilitation.

1 What is a robot?

A robot is a machine capable of adapting to and acting upon its environment thus extending human abilities or replacing them in some activities. It is composed of a mechanical structure made of one or several mechanisms with a certain number of motorized degrees of freedom (DOF) (a DOF is the capacity to make a movement, translation or rotation, around or along an axis in space). It is also fitted with sensors (position, force…) providing it with information regarding its own state as well as information on its environment thus enabling it to carry out a task correctly. It requires two kind of electronic systems: a power system to supply and control the actuators and sensors and a signal processing system to interpret the information from the sensors and to generate commands accordingly. These electronic systems are themselves controlled by one or several programs which constitute the robot's 'intelligence' i.e. how to carry out the task and to react to the environment changes.

Robotic systems used for rehabilitation are called cooperative or co manipulative because there is physical contact between the robot and the human and that despite exchanges which can take place between the two (exchange of forces or sensory information), neither system is completely in charge of the other during the completion of the task. Rehabilitation robots have been developed with the aim of assisting the therapist, by enabling new kinds of "patient adaptative" exercises, by giving an access to precious kinematic and kinetic information and by providing a means to increase therapy time.

2 Robots in rehabilitation

2.1 Advantages of robots

The development of rehabilitation robots has been largely stimulated by recent scientific advances on cerebral plasticity and functional recovery. Nudo demonstrated the capacity of the motor cortex to modify as a result of training following induced hemiparesis in monkeys [NUD 96], termed plasticity. We are also now aware that potential recovery following stroke was previously underestimated. This has been demonstrated by the pioneering work of Paul Bach-Y-Rita [BAC 01] and the results obtained by "Constraint Induced Therapy" developed by Taub and colleagues [TAU 02] showing that functional improvements are possible even several years post stroke.

Studies have shown that therapy should be intense [KWA 99] and repetitive in order to achieve the maximum benefit. However, in order to provide such training, it must be motivating. Exercises should also be designed to promote learning. Robots can easily fulfil these criteria. As tireless systems, they can be coupled with virtual reality environments to provide therapy in the form of games or fun tasks thus motivating patients to spend much time practicing [MIR 08]. Because of their sensors, robots can monitor movement quality as well as progress constantly, providing highly specific feedback to patients to aid learning.

For patients with severe paresis, robots can be used to provide passive movement of the upper limb. Passive movements are known to activate cerebral areas involved in active movements although the benefits with regard to motor recovery are uncertain [LOT 03]. For patients with some movement capacity, robots can support the weight of the limb against gravity [IWA 08] or, due to the physical interaction between the robot and the subject (exchange of forces or 'sharing' of position depending on the type of control system used), they can even assist the movement. This provides a greater opportunity for movement than the patient might otherwise have. Rehabilitation robots aim to help therapists by increasing the duration of rehabilitation exercises, but especially their variety, quality and adaptation to the patient's individual state.

Another very useful feature of robotic systems is the possibility of recording information relating to performance (position, velocity, interaction forces…) during a movement thus providing a very precise quantification of movement-related parameters [ROH 02].

The benefits of robots for rehabilitation are therefore multiple: they can produce repetitive, high quality movements, allowing increased intensity of rehabilitation, they can provide a large variety of exercises for the therapist to choose from and they provide a man-machine-interaction which allows an objective measure of progress, which itself can condition changes in the interaction by altering control parameters.

2.2 Types of robotic systems

Two main types of rehabilitation robots exist. They can be distinguished by the mechanism of human-robot interaction and the number of segments which the robot can directly 'control': manipulanda and orthoses.

Robotic manipulanda are often adapted from industrial robots with more or less degrees of freedom but only one point of physical contact between the distal end of the upper limb and the extremity of the robot (for example, the patient holds a handle or has the forearm strapped to a support). In this category, there are two subcategories: traditional manipulanda (such as the MIT Manus, or the Bi-Manu Track) and cable manipulanda. The MIT Manus is the most famous and has been the object of the most clinical trials. It is a 2 DOF manipulandum with which the patient can interact to make planar pointing movements. During the session, the patient's arm is supported in a non-motorised orthosis and he holds the handle of the manipulandum. Cable robots resemble the classical pulleys used in therapy (NEREBOT, MARIBOT, Kinehaptique, Gentle/s). These types of robots impose forces or positions or provide assistance at the point of contact between the patient and the machine but only at this point. They cannot, therefore, directly control the different movement synergies used by patients in order to achieve the displacement of the endpoint.

More recently, robotic orthoses have begun to be developed. These orthoses allow contact at several key points of the upper limb and can therefore control the different segments of the limb. This means that they can influence coordination patterns and/or better follow the particularities of the patient's postures or movements. There are also two sub-groups in this category: anthropomorphic robots which are in contact practically with the whole limb (exoskeletons such as ARMin, RUPERT and one currently being developed as part of the Brahma project in France (ANR n°173959: BRAHMA [Bio Robotics for Assisting Human Manipulation][1])) [JAR 08], and robots which have discontinuous contact with the limb (ARMguide, Dual Robotic System from Leeds).

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1. http://brahma.robot.jussieu.fr/.

2.3 Principal modes of control

As Marchal-Crespo and Reinkensmeyer explain in a review [MAR 09], the lack of a solid under-standing of how motor recovery can be promoted has led to the ad-hoc development of control algorithms based on some concepts from rehabilitation, neuroscience and motor learning.

Three main modes of control have been used in current studies:

Passive: the patient is inactive and the robot moves his arm. This mode might be useful for preventing muscle contractures but its effectiveness in stimulating motor recovery is doubtful [HOG 06].

Active assisted: the robot partially assists the patient's movement. This movement is useful when patients are able to initiate movement but have difficulty in completing a movement towards a target.

Active constrained: This mode forces concentration, targets particular muscle groups and specific coordination patterns. For example, it is possible to force the patient to use specific postural configurations by commanding the robot only to move when forces are correctly orientated.

A different type of mode is '**bi-manual**': the movements made by the healthy arm are applied in a symmetrical fashion to the hemiparetic arm (which thus receives passive training). This mode exists on a small number of robots such as the MIME.

Modes of control which function under a very different philosophy have also been developed. These are **perturbation**-modes in which the interaction with the robot is not directly beneficial for the task. The robot is controlled in such a way as to perturb the patient's movement in order to stimulate error correction functions essential for motor control [PAT 06].

Most therapy protocols have been designed using an assistive type of control. This has the great advantage of allowing patients to achieve movements they could not otherwise which is highly motivating. Assistance may be triggered once the patient has initiated a movement of sufficient velocity (MIT Manus, ARM Guide) or force (MIME) or when EMG activity reaches a certain threshold. This type of assistance has been implemented using impedance control. Impedance control does not impose a rigid trajectory but allows natural movement variability and small errors to be made. It has 'springy' walls which guide the hand back towards a desired trajectory rather than preventing the deviation in the first place.

Following the philosophy that over-assistance discourages learning, 'assist-as-needed' types of control have been developed, such as Hogan and colleagues' adaptive impedance controller [HOG 04]. This can be described as a 'virtual slot' between the nominal position and the target position. Its walls are springy so as to provide graded assistance to overcome inappropriate movements. The front wall is stationery while the back wall moves along a minimum jerk trajectory [FLA 85]. In this way, if the patient moves faster than the moving wall, he is not assisted, however, if at points of the movement he slows, the wall catches up with him and assists the movement. In 'performance-bases progressive therapy', the robot records kinematic parameters during the patient's movement and is capable of adapting assistance provided to the patient according to his progress.

However, with any assistive type control, there is a danger that patients may 'use' the assistive properties of the robot to achieve the goal with less effort. One way of counteract-ing this may be to provide feedback to the patient reagarging the amount of work he is producing relative to the robot.

For a complete review of control algorithms, see Marchal-Crespo and Reinkensmeyer [MAR 09].

3 Clinical studies

In this section we will describe the principal robots which have now been evaluated beyond the feasibility stage and we will present the results of clinical evaluations for each.
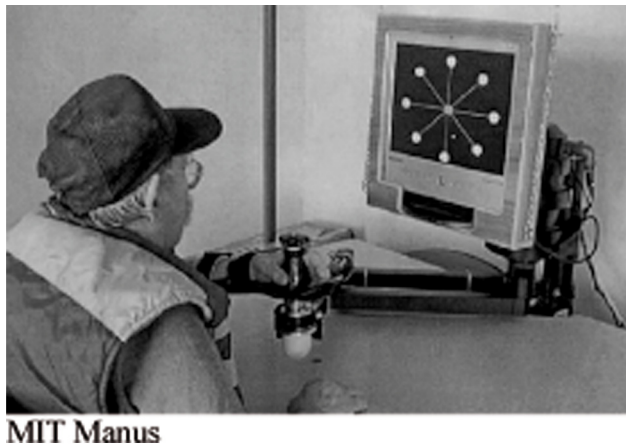

MIT Manus

Fig. 1. From Fasoli S. E., Krebs H. I., et al., "Effects of robotic therapy on motor impairment and recovery in chronic stroke", *Arch Phys Med Rehabil*, vol. 84 (4), pp. 477-482, 2003.

The MANUS robot (now named 'InMotion' and commercialised by MIT in USA) was developed by N. Hogan and H. Krebs [KRE 98] of MIT. This robot, which began its development in the early 90's took over 10 years to become fully operational (Figure 1). It is a 2 DOF system, allowing displacements of the elbow and the shoulder during hand movements made in the horizontal plane. The method of 'impedance' control developed by Hogan [HOG 85] does not impose a rigid trajectory but allows an elastic deviation around the movement programmed by the robot. It is mechanically reversible, allowing the patient to easily move the manipulandum and also allowing the manipulandum to guide and assist the movement.

Several clinical trials have been carried out with the MANUS robot in order to evaluate its effectiveness for rehabilitation of the hemiparetic upper limb. Two studies respectively included 20 and 30 patients all more than 6 months post stroke and no longer undergoing rehabilitation [FAS 03]. Patients were trained over 3 hourly sessions per week for 6 weeks. These un-controlled studies showed some encouraging results with improvements in Fugl-Meyer score (upper limb section), muscle strength and a decrease in spasticity as evaluated by the Ashworth scale. These improvements persisted 3 months later. The benefits appeared to be greatest in patients with a moderate level of impairment compared with those with more severe impairments [FER 03].

A few studies have been carried out in acute stage patients. Volpe et al. [VOL 00] compared the effect of training patients with the MIT-Manus for one hour per day for 5 weeks (in addition to standard therapy) to a control group who only used the robot for one hour per week (during which part of the training was carried out by the ipsilesional limb). The 56 patients all improved but the group with more robot rehabilitation showed significantly greater improvements in motor power and motor score. There was, however, no difference between groups for Fugl-Meyer score.

In a more recent study, the same group [RAB 08] compared twelve 40-minute sessions in addition to standard therapy of occupational therapist led group therapy (OT), cycle ergometer or robot therapy with MIT Manus in moderate-severe subacute stroke patients. There were 10 patients in each group. The OT group carried out a total of 640 movement repetitions, the robot group 1024 repetitions and the ergometer group 2200 repetitions. Despite these different intensities, at discharge, there was no difference between the clinical

scores of the three groups (Fugl-Meyer, FIM, ARAT, motor status score). The authors suggest that although intensive activity-based therapies seem to be important in the treatment of chronic stroke, they may be less important in the acute phase of stroke. Larger studies are, however, needed to confirm this theory.

A very recent randomised controlled trial of 20 patients carried out by the same group [VOL 08] verified if the beneficial effect of robot therapy in chronic patients is the effect of the robot itself or purely to the intense training it provides. They compared equal intensity (i.e. same number of repetitions) training programs of reaching movements carried out either with a therapist or with the MIT Manus. Both groups showed significant improvements on impairment scales by the end of the trial and improvements were maintained at the 3 month follow-up. However, there was no difference between groups. This study very importantly demonstrates that the main effect of the robot on recovery in chronic patients is due to the repetitive nature of the therapy it provides.

To add to the shoulder-elbow training offered by the MIT Manus, the team have developed a 3 DOF wrist trainer which controls wrist flexion-extension, ab-adduction and prono-supination. It can either be used alone or in combination with the Manus. This very importantly offers the possibility of exploring the contribution of proximal versus distal training in improving upper limb function. A study is underway of which the aim is to include 200 patients in 4 groups. All receive 36 sessions of training over 6 weeks. Group 1 train the the shoulder-elbow for the first 3 weeks then the wrist for the next 3weeks, group 2 train the wrist for the first 3 weeks then the shoulder-elbow for the next 3weeks, group 3 train each segment on alternate days and group 4 train both segments within the same session. A paper published results from the first 36 patients included and randomised into group 1 or group 2 training [KRE 07]. Both groups improved but the results suggest that training the more distal wrist first appears to lead to a higher skill transfer to the more proximal segments than vice-versa.
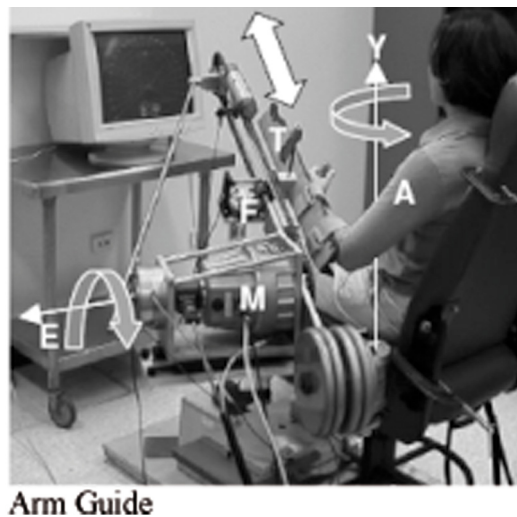

Arm Guide

Fig. 2. From Kahn L. E., Zygman M. L., et al., "Robot-assisted reaching exercise promotes arm movement recovery in chronic hemiparetic stroke: a randomized controlled pilot study", *J Neuroengineering Rehabil*, vol. 3, p. 12, 2006.

The ARM-Guide robot (Assisted Rehabilitation and Measurement Guide, Rehabilitation Institute of Chicago and University of California - Irvine) is a robot which has been designed in order to be simple and inexpensive (Figure 2). The system consists of a handle mounted on a motorized linear slide which can assist the patient's movement. This slide is fixed to

a system with two rotations thus allowing 3D variations in movement orientation. It has 4 DOF. As it is fixed to the patient's hand, the ARM-Guide can provide active assistance to movement and can also function in the active constrained mode. Hand kinematics and forces generated by the patient can also be recorded [REI 00].

A study of 14 chronic hemiparetic subjects compared 24 sessions of traditional rehabilitation over 8 weeks to the same number of sessions with the ARM Guide [KAH 06]. In both groups, subjects made the same number of repetitions of the same pointing movements towards 5 targets. In the 'robot group' (n = 7), the robot provided assistance if the subject was unable to complete the movement or if the movement was too slow. If the subject had a higher level of motor ability then the robot provided resistance to movement. At the end of the study, both groups had reduced the time taken to carry out functional tasks but there was no difference between groups. Reaching distance achieved and path straightness improved equally in both groups during unassisted pointing movements used as a test. Movement smoothness, however improved significantly only in the robot group.
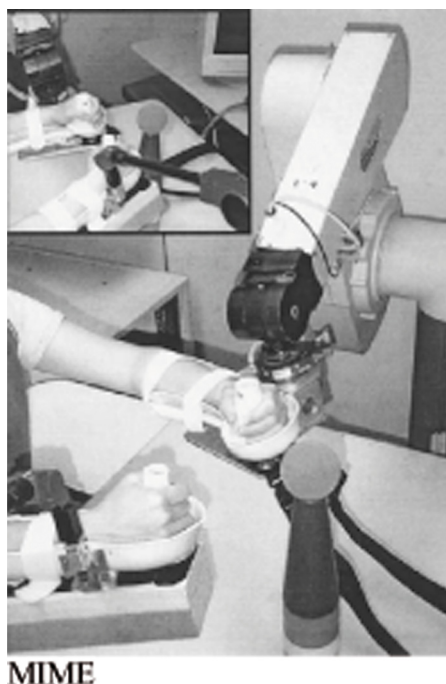

MIME

Fig. 3. From Lum P. S., Burgar C. G., et al., "Robot-assisted movement training compared with conventional therapy techniques for the rehabilitation of upper-limb motor function after stroke", *Arch Phys Med Rehabil*, vol. 83 (7), pp. 952-959, 2002.

The MIME robot (Mirror-Image Movement Enabler, Stanford University and Veteran Administration, Palo Alto) was developed from a classic industrial robot (PUMA 562). The particularity of this robot is that its distal end is fixed in an orthosis in which the patient's arm is placed (Figure 3). As a result of this coupling, the MIME system allows the patient to make large amplitude movements in 3 dimensional space. It contains a 6 axis force sensor which allows interaction forces and moments applied to the patient (and inversely) to be measured at the point of contact between the patient and the robot. As well as the three classical modes of rehabilitation described earlier, the MIME robot uses a bimanual mode during which the robot guides the hemiparetic limb along a trajectory symmetrical to that of the healthy limb.

This robot has been evaluated by Lum and his team. The first study included 27 chronic hemiparetic subjects [LUM 02]. At the end of 24 hourly sessions over 2 months, the patients who were rehabilitated by the robot had significantly greater improvements than the group who received traditional therapy (although this group also improved) for Fugl-Meyer score,

strength and distance reached. The authors noted that these improvements were directly linked to the training (proximal Fugl-Meyer score). The group trained with the robot showed greater increases in muscle strength in the movement directions which were trained. In a later study, the authors suggested that this type of training improves muscle activity patterns [LUM 04]. They base this on the decrease in directional errors, the rapid increase in work and the increase in agonist EMG activity. They suggest that this demonstrates a neural adaptation similar to that observed during strength training in healthy subjects. Rehabilitation with the robot also appears to accelerate recovery compared with traditional therapy (although also intense) even though there does not appear to be particular benefit of the robot therapy after 6 months [LUM 06].

This group also evaluated the specific effect of the bilateral training possible with this robot [LUM 06]. The hypothesis behind this method is that bilateral training specifically stimulates certain neuronal pathways (ipsilateral corticospinal tract, cortico-cortical pathways). 30 subjects were included (1-5 months post stroke). They were classed according to Fugl-Meyer score and lesioned hemisphere and randomized into 4 groups. All the subjects received 50 minutes of rehabilitation per day. The first group used the robot only in unilateral mode (active-constrained) (n = 9), the second group used only the bilateral mode (n = 5), the third group combined the two modes (n = 10) and the fourth group was a control group who received traditional rehabilitation (n = 6). Only the group with the combined training had significantly higher scores than the control group for the proximal arm section of the Fugl-Meyer and the Motor Status Score. This difference was, however, lost at the 6 month follow up. These results must, however, be interpreted cautiously because of the small number of subjects in each group. The authors question the use of bilateral therapy in light of their results and suggest that the benefits of combined therapy may result from the fact that it is less fatiguing.
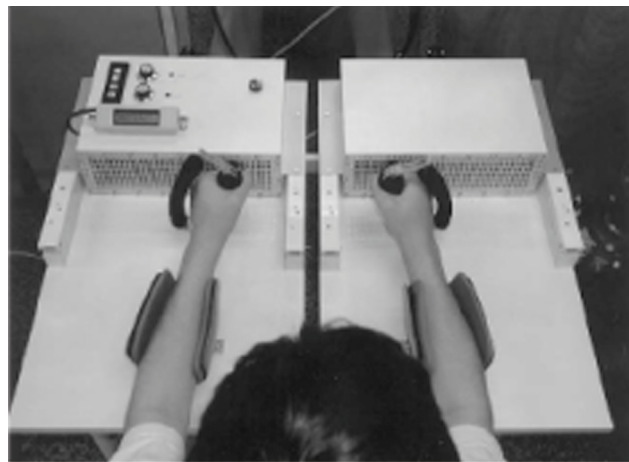
BI Manu Track

Fig. 4. From Hesse S., Schulte-Tigges G., et al., "Robot-assisted arm trainer for the passive and active practice of bilateral forearm and wrist movements in hemiparetic subjects", *Arch Phys Med Rehabil*, vol. 84 (6), pp. 915-920, 2003.

BI Manu Track (Figure 4), commercialised in Germany, consists of double handles which permit unilateral or bilateral training of the distal part of the limb (prono-supination and wrist flexion-extension). It can be used in passive and active assisted modes and the amplitude, speed and resistance of both handles can be set independently. No feedback is given to patients.

44 acute-stage stroke patients were randomly allocated to be trained either with this robot or with electrical stimulation of wrist extensors [HES 05]. These two therapies (each of 20 minutes per day for 6 weeks) were in addition to usual therapy. At the end of the study, Fugl-Meyer and strength (Medical Research Council) scores were greater for the robot-trained group. The difference between the groups was retained 3 months from the beginning of the study. Again, the study design does not allow distinction between the effects of the bilateral nature of the training and the increase in movement repetitions. A previous study showed that that training with the robot can decrease spasticity as measured by the modified Ashworth scale; however, the effect was not maintained after the end of the therapy [HES 03].

Nerobot

Fig. 5. From Masiero S., Celia A., Rosati G., Armani M., "Robotic-assisted rehabilitation of the upper limb after acute stroke", *Arch Phys Med Rehabil*, vol. 88, pp. 142-149, 2007.

NeRoBot (NeuroRehabilitation Robot) is a 3 DOF wire-robot, which makes it cheaper than a classical robot (Figure 5). It is can be used in a sitting or lying position. Exercises incorporating shoulder flexion-extension, ab-adduction and circumduction, elbow flexion-extension and prono-supination can be carried out. The therapist moves the patient's arm in the direction which he is to practice. The robot records and subsequently repeats the movement. Visual feedback via a 3D representation of the patient's arm on a screen informs him of the desired movement direction to guide his movement.

A study carried out on 17 patients during the acute-phase of stroke showed that the addition of 4 hours of rehabilitation per week with the NeRoBot significantly improved Fugl-Meyer score (proximal), deltoid and biceps strength in comparison with 18 patients who received standard therapy. The difference was maintained at the 3 and 8 month follow-up sessions [MAS 07].

Haptic Master

Fig. 6. From Amirabdollahian F., Loureiro R., et al., "Multivariate analysis of the Fugl-Meyer outcome measures assessing the effectiveness of GENTLE/S robot-mediated stroke therapy", *J Neuroengineering Rehabil*, vol. 4, pp. 4, 2007.

The Haptic Master (Figure 6) is a 3 DOF robot designed by Fokker Control Systems (FCS) and is the basis of an European Union project entitled GENTLE/s. This robot was developed from a haptic virtual reality system, completed by a cable suspension system. It uses the three principal control modes: passive, active-assisted in which the patient's movement is assisted following initiation of appropriate forces and an active mode in which the robot only corrects deviations from the trajectory but does not assist correct movement. Along with the robot, a large variety of exercises have been developed in a 3D virtual environment giving the patient and therapist the possibility of choosing and adjusting the training parameters. Performance feedback is provided to the patient. A study was carried out in 31 hemiparetic patients in the chronic stage of stroke comparing this robot with sling-suspension exercises. After a total of 4.5 hours of training, both groups had improved Fugl-Meyer score but there was no evidence that the robot therapy was better than suspension therapy [AMI 07].

A later study used an ABC or ACB design also comparing robotic therapy with sling therapy (A = baseline, B = robot, C = sling). 20 subacute-chronic stroke patients were randomly allocated to one of the trial orders. The results showed that robot therapy appeared to speed up the rate of recovery [COO 08].

The Reharob project (Figure 7) coordinated by the Budapest University of Technology and Economics uses a different approach from the majority of the research teams working on the coordination of joint motion. Instead of developing a complex orthotic device, they developed a system in which upper limb motion therapy is driven by industrial robots using intelligent identification of the required physiotherapy motions [TOT 05]. The system is composed of two industrial A.B.B. robots. The end effector of one is connected to the patient's forearm and the end effector of the other to the patient's upper arm (both through a force sensor and a security lock mechanism which limits the forces exchanged) and can be co-manipulated by the therapist by means of a handle placed on the end effector, to teach the robot the therapy movement it will reproduce during the session. Contrary to other systems which aim to provide goal-directed movements, the aim of Reharob is to provide a high number of slowly executed movements with a constant velocity to decrease spasticity and increase range of shoulder and elbow motion.

An initial trial demonstrated that the robotic system worked safely and reliably, that patients were not afraid of the robot and that physiotherapists had no difficulty in learning how to operate the system (Fiziorobot project) [TOT 05]. Some modifications were made

REHAROB

Fig. 7. From Toth A., Fazekas G., Arz G., Jurak M., Horvath M., "Passive Robotic Movement Therapy of the Spastic Hemiparetic Arm with REHAROB: Report of the First Clinical Test and the Followup System Improvement", *Proceedings of the 2005 IEEE 9th International Conference on Rehabilitation Robotics June 28 - July 1, 2005*, Chicago, IL, USA, 2005.

to the system's force controller, the graphical user interface, the instrumented orthoses, and the patient enabling device. A randomised controlled clinical study was then carried out with 30 chronic hemiparetic patients divided into a robotics group and a control group [FAZ 07]. Patients in both groups received 30 minutes of Bobath-therapy on each of 20 consecutive workdays. The robotic group received an additional 30 minutes of robot-mediated therapy on each of the same 20 days. There was some reduction in elbow flexor spasticity (modified Ashworth scale) in both groups but not in shoulder adductor spasticity and both groups also increased elbow range of motion but not shoulder. Both groups improved the shoulder-elbow sub-section of the Fugl-Meyer test as well as FIM score. Improvements were more in favour of the robot therapy although the differences were not significant.

T-WREX (Figure 8) is a passive instrumented arm orthosis (Therapy Wilmington Robotic Exoskeleton) that enables individuals with hemiparesis to exercise the arm by playing computer games in a gravity-supported environment [SAN 06]. It contains a pressure-sensitive hand grip, enabling hand grasp to be incorporated in the activities. It is linked to a computer interface with games specifically designed to train different types of 3D movements and to provide performance feedback to the patient. DOF can be locked to prevent unwanted movements such as shoulder abduction. It can be attached to a wheelchair and thus is very portable.

Following a study to evaluate the effect of providing gravity support to the hemiparetic arm which showed that co-contractions decreased and movement parameters such a smoothness improved [IWA 09]. The study compared semiautonomous training with T-WREX with conventional semiautonomous exercises that used a tabletop for gravity support. Twenty-eight chronic patients with moderate/severe hemiparesis were included. At the end of twenty-four
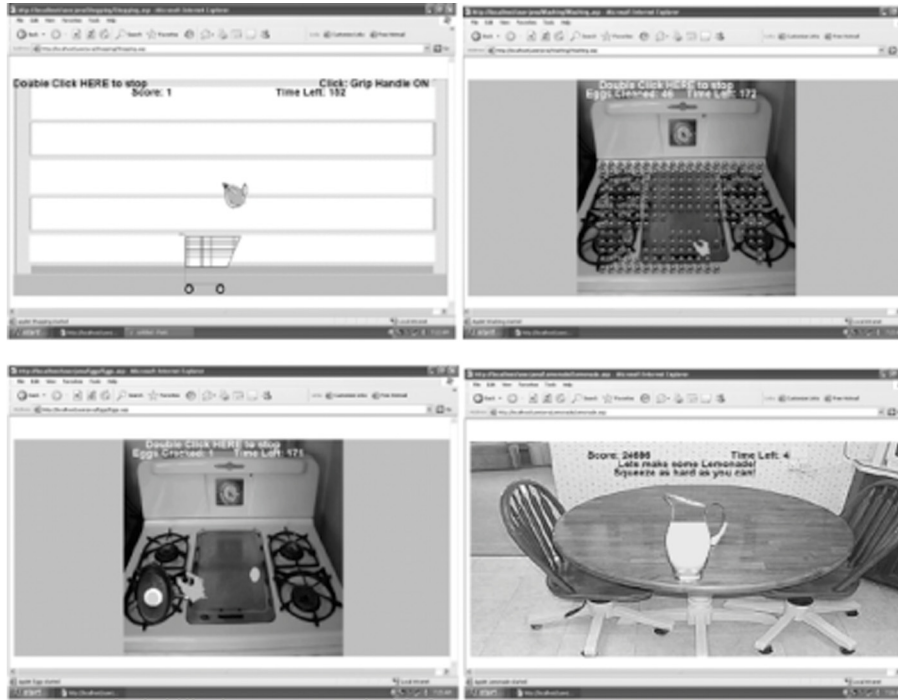
Example of rehabilitation games used with the T-WREX.

Fig. 8. From Sanchez R. J., Liu J., et al., "Automating arm movement training following severe stroke: functional exercises with quantitative feedback in a gravity-reduced environment", *IEEE Trans Neural Syst Rehabil Eng,* vol. 14 (3), pp. 378-389, 2006.

1-hour treatment sessions, all subjects improved significantly in upper extremity motor control (Fugl-Meyer), active reaching range of motion, and self-reported quality and amount of arm use (Motor Activity Log). Improvements were sustained at 6 months. The T-WREX group maintained gains on the Fugl-Meyer significantly better than controls at 6 months. Subjects also reported a preference for T-WREX training.

3.1 Current conclusions on the effectiveness of robotic therapy

Two recent systematic reviews [KWA 08] of randomized controlled trials evaluating rehabilitation robotics found similar results: robotic rehabilitation improves motor function of the impaired arm as well as strength but these improvements do not transfer into activities of daily living. The general conclusions were that robotic therapy is effective; however, when delivered at the same intensity as traditional therapy, it is not more effective. As was pointed out by Kwakkel [KWA 08], in these studies, the robots were principally used for their ability to provide a large number of repetitions. For this reason, it is hardly surprising that, for equal doses, robots do not provide anything more than therapists.

However, this 'at-least-as-good-as' result is important. It is widely accepted that 'more is better' as far as therapy is concerned, even if how much more is uncertain. Coupling of rehabilitation robots with fun, motivating virtual reality interfaces is an excellent manner to increase intensity of rehabilitation [COL 07, HOL 05]. This has important implications with regard to the capacity of therapy services to deliver higher intensity therapy. If robots are as good as therapists and can provide a means to deliver more therapy, this has obvious advantages for patients.

4 Which mode of control?

An important question is: is robotic therapy limited to the provision of a great number of movement repetitions or does it have other potentials? Robots may have 'skills' which therapists do not because of the different sensors they contain and their high level of precision. It is very tempting to believe that they can be used to develop highly specific training for the kinematic and dynamic impairments which patients have.

A few studies have compared the effects of different types of control on movement and motor recovery. Two modes of control (active-assisted and progressive-resistance) were specifically compared using the MIT Manus robot in a study of 46 chronic hemiparetic patients [STE 04]. The subjects carried out 1024 movements per session and 18000 over the whole protocol. Although both groups improved significantly, there was no difference between the groups. This result is in line with other studies in stroke patients showing that the factor which influences motor recovery is the task-oriented training and not strength training [MOR 03].

Kahn et al. [KAH 06] also compared two modes of control (active-assisted and an active-constrained mode which required forces to be correctly directed for movement). They did not find any differences with regard to function but they found that the active constrained mode improved movement quality. They suggest that guiding correct use of forces via the robot is fundamental because it helps the subjects to relearn sensori-motor transformations which are necessary for reaching movements.

A few groups have studied adaptation when the arm or hand is subjected to a force field. It is known that healthy subjects are capable of adapting to this type of perturbation: they learn to move the endpoint in a straight line despite deviating perturbations [SHADMEHR and MOUSSAVI2000]. Patton [PAT 06] demonstrated that hemiparetic patients are also capable of short-term adaptation to force fields (although the adaptation is not as strong as in healthy subjects). A very interesting phenomenon is that this adaptation is greater in force fields which amplify rather than correct errors. One hypothesis is that, in patients, errors are intrinsically linked to learning mechanisms and therefore to clinical improvements in motor ability. Further studies are necessary in order to fully understand the effects of force fields on hemiparetic patients.

Much research is still needed in order to fully evaluate the effects of these different modes of control. It seems likely, however that, like more classical therapy techniques, different modes might be useful for patients with different levels of impairment and at different stages of recovery.

Conclusion and perspectives

The great advantage of robots is that they can provide highly standardized rehabilitation protocols in which a multitude of parameters can be quantified (number of repetitions, kinematics, modifications in movement parameters over sessions…). This feature is extremely useful for studies attempting to understand the effect of lesion size and location on rehabilitation and the recovery process [KRE 09]. For the same reasons, robots are also useful tools for examining the effect of new interventions such as brain stimulation [EDW 09] or, pharmacological agents etc.

The ability of robots to provide quantitative assessment of movement kinematics makes them useful for increasing understanding of motor control and learning. Rohrer and collegues [ROH 02] showed that after stroke, kinematics of the endpoint (hand) appear to be

characterised by the presence of submovements. They suggest that the progressive blending of these submovements is what underlies motor recovery.

The studies described in this paper all show that robotic rehabilitation is feasible and safe. Although there is a growing number of randomised controlled trials which have evaluated the effect of robots in rehabilitation, high quality studies with large numbers of subjects are lacking [KWA 08]. There is, however, evidence that as part of a rehabilitation program, robots can contribute to improving motor ability of the upper limb in hemiparetic adults.

A provisional conclusion in the light of current research is that robots have both a quantitative and a qualitative advantage. On the quantitative side, they provide more intense training than is currently possible in most rehabilitation programs. They have the advantage of facilitating exercise in well controlled, reproducible conditions. Qualitatively, certain modes of control appear to be more effective than others but the mechanisms behind this effectiveness remain within a 'black box'. Robotic systems can provide a means of therapy for patients with severe impairment who cannot take part in other rehabilitation methods such as constraint induced therapy. However, very few studies have evaluated patients in the acute phase or attempted to design specific programs for patients with severe impairment.

The results from studies are also difficult to generalize because of the heterogeneity of existing robots and control modes used, the differences in types of exercises and also because the majority of robots are non-commercialized prototypes.

A limitation of most robots is that they do not allow training in full range of joint motion and with all the necessary DOF [TIM 09]. Several research groups are currently working on the development of robotic orthoses or exoskeletons which can control each segment of the upper limb and therefore rehabilitate specific components of 3D movements such as inter-articular coordination. This type of robot can also be used as a 3D isokinetic device allowing forces generated by patients during multi-articular movements to be quantified. This could provide a highly pertinent form of functional evaluation.

Another limitation of current robots which needs to be developed is the fact that they only retrain the transport component of reach to grasp movements. The results of the studies discussed here show that improvements occur mostly in the proximal arm segments which were trained but the improvements do not generalize to the rest of the limb. Future developments may be towards 'assisted hybrid systems' as Popovic et al. [POP 05] suggest. They propose that the combination of a robotic system with at least 6 DOF allowing the hand to be orientated, with functional electrical stimulation of hand muscles to assist in grasping could be useful for functional rehabilitation of the limb as a whole.

In order to combat cost-related problems relating to transport of patients to rehabilitation centres, therapist time etc., a new mode of rehabilitation delivery has been conceived. This is tele-rehabilitation which makes the most of internet connections. Robotic systems are essential for this mode of delivery. Various systems are being developed in which the therapist can supervise several patients at a distance, following their progress and managing exercise programs or even interacting with them [CAR 06]. This is an important step towards providing therapy to more patients for longer periods of time and thus giving stroke patients a better chance of recovery.

In summary, robotics for rehabilitation appear to have definite advantages: repetition of quality movements, the possibility of assisting movement and objective evaluation and the potential for better control of synergy recovery with future robotic orthoses. It is therefore probable that the role of rehabilitation robots will become essential in rehabilitation programs which aim to provide intensive therapy. This quantitative aspect will likely progress in the future along with developments in research in the field of robots.

Acknowledgements

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