Upper and lower extremity robotic devices for rehabilitation and for studying motor control

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Purpose of review

The successful motor rehabilitation of stroke, traumatic brain-injured and spinal cord-injured patients requires an intensive and task-specific therapy approach. Budget constraints limit a hand-to-hand therapy approach, so that intelligent machines may offer a solution to promote motor recovery and obtain a better understanding of motor control. This new field of automated or robot-assisted motor rehabilitation has emerged since the 1990s.

Recent findings

This article will present clinically viable devices for upper and lower extremity rehabilitation. The MIT-Manus and the Mirror-Image Motion Enabler robot, which enable unrestricted unilateral or bilateral shoulder and elbow movement, consistently proved superior on the motor impairment level. The ARM guide, which assisted reaching in a straight-line trajectory, and the Bi-Manu-Track, which enabled the bilateral practice of a forearm and wrist movement, are currently being tested. For gait rehabilitation after stroke, the electromechanical gait trainer, GT I, has proved effective compared with treadmill training with body weight support. The Lokomat, consisting of a treadmill and a powered exoskeleton, lessened the therapeutic effort compared with manually assisted treadmill training in spinal cord-injured patients. Future developments will see more degrees of freedom, improved man–machine interaction and the implementation of virtual reality.

Summary

Technical possibilities are one aspect, but multi-centre trials and a consideration of the unsubstantiated fears among therapists of being replaced by machines will decide on the successful implementation of this most promising field to the benefit of patients.

Keywords

lower extremity, motor rehabilitation, stroke, upper extremity

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Abbreviations

BWS	body weight support
DoF	degree of freedom
FM	Fugl–Meyer
RCT	randomized controlled trial
SCI	spinal cord-injured

1350-7540

Introduction

Stroke, traumatic brain and spinal cord injuries are a leading cause of disability and handicap in the industrialized world. Stroke patients are the largest group, with 750 000 individuals affected in the United States each year, the prevalence being 200–300 patients/100 000 inhabitants [1].

To improve arm and gait ability after a brain lesion, an early and intensive therapy approach is advocated. The intensity of the arm and leg therapy positively correlated with the motor outcome after stroke [2], and task-specific and goal-oriented repetitive approaches, such as constrained–induced movement therapy [3] and treadmill training with partial body weight support (BWS), proved effective [4,5].

In daily practice, however, budget constraints limit an intensive hand-to hand therapy programme. Accordingly, intelligent machines may offer a solution to increase the intensity of therapy. Ideally, a sophisticated man–machine interaction should try to simulate the experienced hand of the therapist guiding the paretic limbs in a gentle manner, avoiding abrupt perturbations and providing as little assistance as necessary. Further potential advantages are therapy documentation within quality programmes and the study of the principles of motor control.

This new field of automated or robot-assisted motor rehabilitation has emerged since the 1990s and is rapidly developing. The present article intends to offer a scrutinized review of recent developments in robot-assisted upper and lower limb rehabilitation, including an outlook into future developments. The vast field of manipulative robots for severely disabled patients will not be covered.

Upper limb rehabilitation

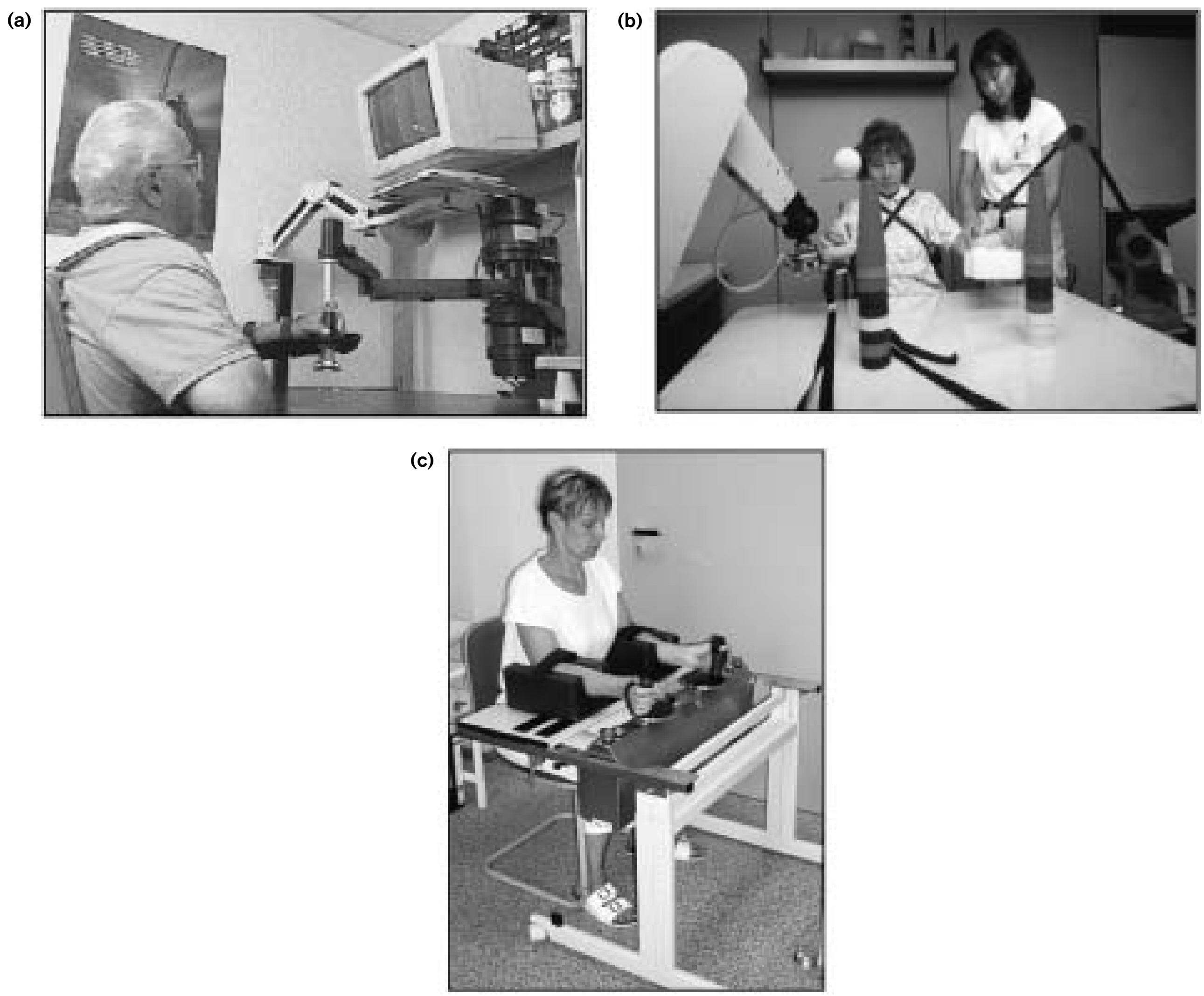
Our motor system enables the selective movement of the shoulder, elbow, wrist and finger joints in multiple ways, either isolated or within movement chains. No machine can compete with this incredible movement variety at present, and any additional degree of freedom (DoF) of any applied robot arm causes exponential costs. A restriction of movements to be practised was thus inevitable, nevertheless aiming at a generalized motor recovery of the whole upper limb. Most groups concentrated on shoulder–elbow movements, with the forearm and hand attached to a splint.

Hogan and co-workers [6] were the first to introduce the MIT-Manus device, a two DoF robot enabling unrestricted movement of the shoulder and elbow joint in the horizontal plane. Impedance control intended to simulate the manual guidance by the experienced therapist gave it a soft, compliant feel during movement. A video screen displayed the trajectories to be followed by patients. Currently, the group is developing a three DoF wrist manipulator (Figure 1a).

For evaluation of the two DoF MIT-Manus, the group conducted several randomized controlled trials (RCTs) on a total of 96 acute hemiparetic subjects for an average of 2 weeks after their first single stroke [7–10]. Patients in the experimental group received robotic training for at least 25 h (1 h/workday, 5 days a week) with a minimum of 1500 repetitions of goal-directed movements over the whole treatment period. The control group was exposed to the robot 1 h per week in such a way that the non-affected limb itself performed the movement or assisted the affected extremity. The robot was never active.

By the end of the treatment, the robot group's motor power for the trained shoulder and elbow was significantly larger, the strength of the untrained wrist and hand did not differ. The Fugl–Meyer (FM) motor score (0–66) assessed the motor function of the affected upper limb. Both groups showed comparable improvements with a median of 4–6 points. A significantly larger

Figure 1. Robots for the training of the upper extremities



(a) MIT-Manus; (b) MIME; (c) Bi-Manu-Track.

improvement in the competence in daily activities in the robot group at the end of the treatment (functional independence measure 25.0 versus 19.5 points), was only described for a subgroup of 76 patients; however, the experimental group had scored significantly higher at the start of the study (30.5 versus 21.5 points). Follow-up evaluations for up to 3 years for 31 of the 96 patients revealed sustained elbow and shoulder motor power gains in the upper limb compared with the control individuals.

Most recently, the group reported on 20 chronic patients with a single unilateral stroke within the past 1–5 years; the initial mean FM scores (0–66) were approximately 30 [11••]. Robotic therapy was provided three times a week for 6 weeks. The authors offered two forms of robotic therapy: sensorimotor or a newly introduced progressive resistive programme. Subjects who could not move the robot handle to all targets participated in the sensorimotor group, i.e. the robot provided movement assistance. Subjects who were initially able to reach all targets were randomly assigned to the sensorimotor or the progressive resistive therapy group. In the latter, the subjects moved the handle against an opposing force according to their abilities. Both groups improved proximal muscle strength and motor function, with a mean gain of 3.5 FM points. The progressive resistive group experienced improvements in the motor power score of the untrained wrist and hand that were not observed in the sensorimotor group nor in the previous RCT on acute patients (see above).

The mirror-image motion enabler (MIME) robot, presented by Burgar and co-workers at Stanford University [12], consisted of a commercial six DoF robot arm attached to a forearm splint. The current workstation enabled the bilateral practice of a three DoF shoulder–elbow movement with the non-paretic arm guiding the paretic one according to a master–slave principle with the help of a six DoF position digitizer. The forearm could be positioned within a large range of positions and orientations in three-dimensional space. Four therapy modes were programmed: passive mode; active-assisted mode with the patient initiating the movement and working with the robot; active-constrained movement with the robot providing a low resistance in the direction of the desired movement and spring-like forces in all other directions; and bimanual. In the bimanual mode, the non-affected extremity guided the affected one in a mirror-like fashion. The bilateral mode aimed at the facilitation of the affected hemisphere via intercallosal fibres (Figure 1b).

Lum and co-workers [13••] conducted an RCT with 27 chronic (>6 months post-ictum) hemiparetic patients allocated to two groups. All subjects received 24 1 h sessions over 2 months. Subjects in the robot group practised shoulder and elbow movements while assisted by the robot. Subjects in the control group received a neurodevelopmental therapy targeting proximal upper limb function and 5 min of exposure to the robot in each session.

Both groups were homogeneous at the start of the study with respect to major clinical characteristics and outcome variables. Compared with the control group, the robot group had larger improvements in the proximal movement portion of the FM test after 1 and 2 months of treatment. Starting from a mean total score of 24.8 (26.6), the robot (control) group had gained 3.3 (1.6) points within 2 months. The robot group also had larger gains in proximal arm strength and larger increases in reach extent after 2 months of treatment. At the 6-month follow-up, the groups no longer differed in terms of the FM test; however, the robot group had larger improvements in the competence of daily activities. Muscle strength and reach were not assessed at follow-up.

The results only partly compared with the large RCT on the MIT-Manus; the MIME study included chronic instead of acute patients and was able to show a superior improvement of motor functions assessed with the help of the FM test in the robot group. The authors speculated that the bilateral and active-constrained modes may have yielded these favourable results. The higher competence of the robot group in daily activities at follow-up was unexpected; with no further improvement of the proximal arm function of the affected side in the same period it may have been caused by better compensatory movements with the non-affected extremity.

Less sophisticated devices were the ARM-guide and the newly introduced Bi-Manu-Track arm trainer. The ARM-guide for the evaluation and treatment of hemiparetic patients assisted reaching in a straight-line trajectory using a linear constraint with a single motor [14]. Active assist exercise (three times a week for 2 months) of three chronic patients resulted in a reduction of muscle tone in two severely affected patients, whereas reaching on the constraint and in free space did not show major changes at the end of therapy.

The Bi-Manu-Track trainer followed the bilateral approach, enabling the bilateral passive and active practise of two movements: a forearm pro/supination and wrist flexion and extension in a mirror-like or parallel fashion [15•]. The amplitude, speed and resistance of both handles could be set individually. The first open study included 12 severely affected chronic patients (>6 months post-ictum), who suffered from at least moderate wrist and finger spasticity and could merely move the shoulder and elbow joints. Three weeks of daily therapy for 30 min resulted in a muscle tone reduction for one to two scores on the Modified Ashworth score (0–5) and proximal muscle functions improved in five out of the 12 patients without a carry-over effect in daily practice (Figure 1c).

Most recently, the first clinical data were reported for the GENTLE/S robot [16•]. It comprised a three DoF haptic interface arm, and an overhead system supporting the upper extremity in a wrist and elbow orthosis for gravity control. Nineteen chronic patients either followed an A–B–C or an A–C–B design, with A: baseline; B: robot therapy three times a week; and C: de-weighted sling therapy three times a week. Each phase lasted 3 weeks. In both groups the rate of recovery was greatest during the B-phase of robot-mediated therapy, the slopes for the FM score were 0.08 across the baseline, 0.43 across the B, and 0.28 across the C phase. However, the level of impairment and the time since the onset of stroke were broad in both groups, the initial FM score for instance ranging from 4 to 59.

Projects in a pre-clinical stage are the NeRebot, a wire-based three DoF robot for the passive movement of the upper extremity in the initial flaccid stage [17], and the REHAROB, consisting of two six DoF industrial robots for the controlled passive movement of the upper and lower part of the upper extremity in 45 catalogued exercises [18].

Lower limb rehabilitation

The movement of the lower limbs during locomotion is rather stereotypical, at least in the sagittal plane and is thus suitable for machine support. The weight of the patients and the necessary acceleration of body mass, for example during push-off, pose the major problems.

Hesse and co-workers [19] presented the electromechanical gait trainer, GT I, aimed at relief of the strenuous effort of therapists during locomotor therapy on the treadmill when setting the paretic limbs (Figure 2a).

The harness-secured patient was positioned on two foot-plates, whose movements simulated the stance and swing phase in a physiological manner. Step length and cadence could be set individually, and ropes attached to the harness controlled the movement of the centre of mass in the vertical and horizontal direction in a phase-dependent manner. Functional electrical stimulation of the thigh muscles during the stance phase assisted knee extension during the stance phase. Gait analysis showed that sagittal joint kinematics and the muscle activation pattern of various lower limb muscles of hemiparetic patients corresponded to each other on the gait trainer and on the treadmill. On the machine, patients walked more symmetrically, with less spasticity, and the vertical centre of mass displacement was more physiological.

A first baseline treatment study [20] included 12 chronic non-ambulatory hemiparetic patients (>6 months post-ictum). Four weeks of additional daily therapy at 20 min on the machine resulted in a marked improvement of gait ability and muscle activation compared with the preceding 3-week baseline of conventional therapy. During a single 20-min session, the patients practised 800–1000 steps.

Next, a randomized cross-over study included 30 non-ambulatory subacute hemiparetic patients randomly allocated to two groups, A and B, who either followed an A–B–A (group A) or an B–A–B design (group B) with A equals 2 weeks gait trainer and B equals 2 weeks treadmill. One instead of two therapists was required on the machine. Gait ability improved steadily in both groups, with patients in group A walking significantly better (i.e. more independently) during the last phase. Gait velocity did not differ between the groups. At follow-up the effects had waned [21••].

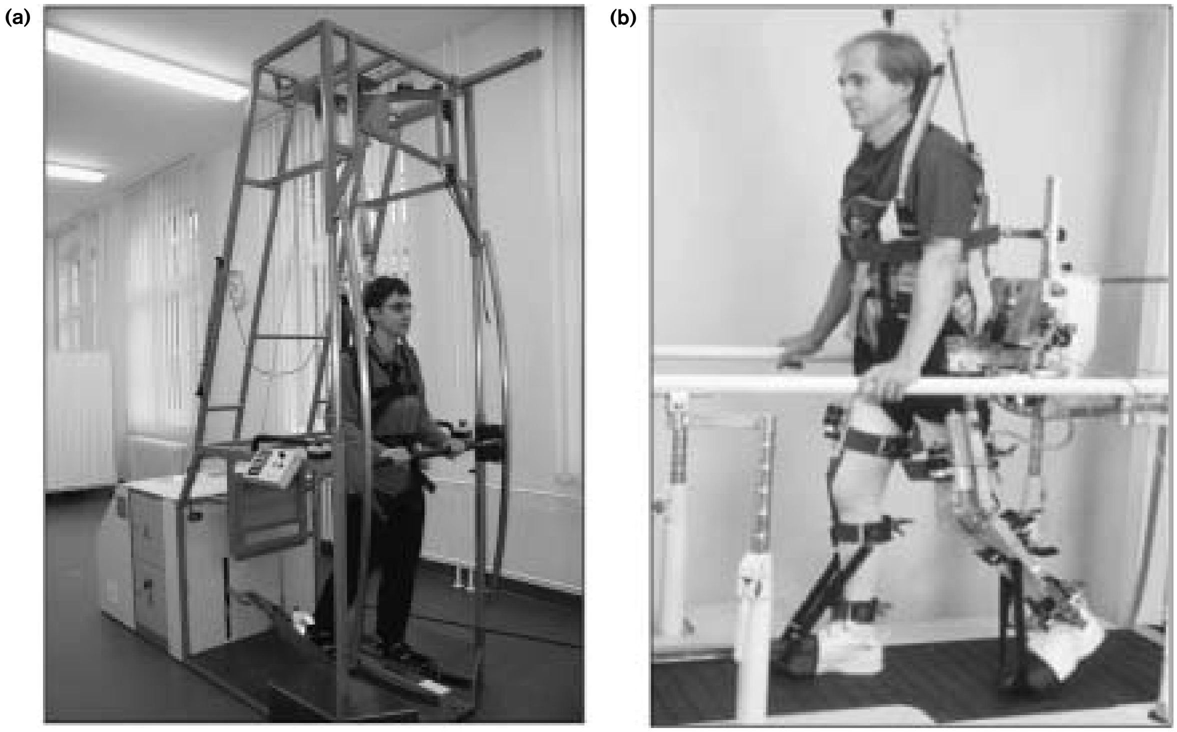
Colombo and co-workers [22] combined a treadmill with a driven gait orthosis (Lokomat) for the locomotor treatment of spinal cord-injured (SCI) patients. The adjustable exoskeleton included position-controlled actuators at the knee and hip joints to secure the swing phase, while the treadmill provided the stance phase. The ankles were set passively. The exoskeleton was fixed to the railing of the treadmill by a rotatable parallelogram. This set-up allowed the upward and downward movement of the body and the sagittal movements of the lower limb joints. SCI patients could tolerate the automated training for up to 60 min, whereas the manually assisted therapy on the treadmill only lasted 10–15 min. Two SCI patients, one incomplete level C3 and one complete level C5, exhibited similar electromyographic activities of various lower limb muscles during the manually assisted and the automated gait training [23] (Figure 2b).

In a preclinical stage were powered exoskeletons: a robot arm directly manipulated the ankle joints on the treadmill [24], a six DoF wire system controlled the trunk movements in any direction [25], and a system with programmable foot plates allowed the practise not only of walking but also stair climbing [26].

Future developments

Future technical developments will see more DoFs, improved man–machine interaction, biofeedback appli-

Figure 2. A left hemiparetic patient practising walking on the gait trainer, GT I (a), and a paraparetic patient practising walking with the Lokomat (b)



cations, the integration of virtual reality, and minimized actuators based on different technologies. Technical possibilities (and enthusiasm) seem unlimited, but any new piece of technology has to be tested with respect to safety requirements, effectiveness and efficiency.

What is the present level of evidence and where will the future go? Among the lower limb devices, the Lokomat has not yet been tested. For the electromechanical gait trainer, GT I, one cross-over study, conducted by the group also responsible for its design, positively evaluated the machine compared with treadmill training with BWS. To escape any bias effects, multi-centre studies must be the next step. Immediate technical challenges are the implementation of force control (to lessen the opponents' major argument of a purely passive therapy) and the possibility of practising an individualized instead of a stereotypical gait pattern. The future will surely see machines for the repetitive practice not only of floor walking but also of stair climbing up and down, and the simulation of sudden perturbations.

Among the upper limb robots, the MIT-Manus and the MIME proved consistently favourable at an impairment level in well-designed RCTs. Future studies need to address the disability level (e.g. the use of the hand in daily life, pain relief or the ease of cleaning the spastic hand) to a larger extent. For the concept of future developments, the more favourable result of the MIME (with respect to the FM improvement) and of the progressive resistive mode of the MIT-Manus (with respect to a stronger muscle power of the untrained wrist and hand) need to be considered. The results are in accordance with physiotherapists' experience that patients' active participation is a stronger facilitatory drive compared with a more passive therapy. Furthermore, mirror-like movements (see MIME and Bi-Manu-Track robots) are another well established factor promoting motor recruitment of the paretic muscles. A distal versus proximal approach in robot-assisted upper limb rehabilitation will be another issue; arguments in favour of a more distal approach may be the larger cortical representation of the forearm and hand, and the presumed competition of proximal and distal body segments for recovery.

Conclusion

Last but not least, the successful clinical implementation of this new fascinating area needs to address fears that the robot will replace the human work force, and that it will 'dehumanize' the rehabilitation of our patients. It must be clear right from the beginning that machines are intended to be an adjunctive tool to increase the intensity of therapy in line with modern principles of motor rehabilitation. A robot can never replace the multi-level interaction between patients and therapists, nor mimic the sensor-motor abilities of the hand of the experienced therapist. On the other hand, automated motor rehabilitation can offer new fascinating aspects in treatment, diagnosis, and interdisciplinary cooperation to the benefit of all participants.

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