ORIGINAL ARTICLE

Robot-Assisted Upper and Lower Limb Rehabilitation After Stroke

Walking and Arm/Hand Function

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SUMMARY

Introduction: Robots help to intensify motor rehabilitation of the upper and lower limbs after stroke. This article presents controlled studies relating to this topic, and an overview.

Methods: A search was carried out for relevant randomized controlled trials, published between 1980 and 2007, on Medline (PubMed), Embase, and CINHAL.

Results: Two studies showed benefit for an electromechanical gait trainer, with significantly more patients resuming walking as compared to conventional physiotherapy. Two studies showed no evidence of benefit for an exoskeleton-based system. A pooled analysis was not conducted due to the small numbers of studies and high heterogeneity. In arm/hand rehabilitation a number of unilateral or bilateral end-effector based systems proved effective in patients with stroke, and a simple one-dimensional system and a passive exoskeleton system proved effective in patients with chronic symptoms.

Discussion: Robot-assisted motor rehabilitation after stroke appears promising. More trials, including comparative studies, are mandatory. The robot cannot be considered a substitute for the patient-therapist relationship.

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Key words: stroke, hemiparesis, rehabilitation, robotics, physiotherapy

Every year, more than 200 000 people in Germany suffer a stroke. Restoration of walking ability and arm/hand function is an essential objective of rehabilitation.

Three months after the stroke, about a quarter of the patients are still bound to the wheel-chair. In 60% of patients, the gait becomes slower to a degree which is practically important in normal life. About 30% of patients suffer from loss of function in an upper extremity (1).

Bobath therapy is the most frequently used form of treatment in Germany. This aims at normalizing muscle tone and restoring physiological coordination in as far as possible. This therapy has been found to be equivalent, or – in one case – inferior, to other physiotherapeutic techniques (functional therapy, proprioceptive neuromuscular facilitation [PNF], "motor relearning" programs, arm ability training) (table 1). The largest study included 282 acute patients in three groups (2). In addition to 45 min Bobath therapy daily for four weeks, two groups of patients were given two hours of therapy per week, either from a Bobath therapist or from an assistant. There was no difference between the three groups at the end of therapy.

To intensify gait rehabilitation after stroke (3), treadmill therapy with partial body weight support was introduced at the start of the 1990s (4). However, this has the disadvantage that the therapist's physical activity remains high. According to a meta-analysis, treadmill therapy for stroke patients was not superior to conventional therapy (5).

To intensify gait rehabilitation without excessive exertion from the therapist, gait trainers have been used since the late 1990s.

The development has been similar for the upper extremities, particularly for severely affected patients, who cannot take part in favorably evaluated programs, such as the forced use of the affected hand (6) or arm ability training (7).

In this review article, the authors summarize the current state of knowledge of the success of robot-assisted rehabilitation.

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Methods

In the course of June 2007, the authors undertook a systematic literature search for articles on the theme of "robot-assisted upper and lower limb rehabilitation after stroke" which had appeared within the period from 1980 to March 2007 (8). The databases were PubMed/Medline, Embase and CINHAL (*box*).

Conventional systems of evaluation

The "functional ambulation category" (FAC), with values from 0 to 5, is an established scale to evaluate the walking ability of hemiparetic patients (9). Level 0 signifies that the patient cannot walk even with help. Level 5 signifies a patient who can walk everywhere, including stairs. From level 3, the patient can walk independently on a plane, but must be accompanied.

The Fugl-Meyer score (0 to 66) is an established scale to evaluate the locomotor control of the upper limbs (10).

Statistics

The results for gait rehabilitation were analyzed.

The first outcome parameter was walking ability at the end of the study. This is defined as FAC >3, or in a comparable manner. The study effects are the chance of being able to walk again (odds ratio, OR). If OR >1, this means that there is an increased chance of being able to walk again.

The second outcome parameter was the walking speed in m/s. The effects of all included studies were

illustrated in a Forrest plot. The authors did not perform a pooled meta-analysis, because of the heterogeneity of the study results.

Results

Gait rehabilitation

The movement of the legs during walking does not vary much and is suitable for system support. The main problems lie in the patients' weight and in the acceleration.

Five controlled studies were identified (*table 2*). Colombo et al. of Zurich (11) developed a so-called exoskeleton (11). This consists of a treadmill and an exoskeleton, with rods and joints modeled on the skeleton of the legs and which can be fitted to the dimensions of the body. Programmable drives are integrated. These can actively flex the hip and knee joints during the swing phase of the legs. The feet are moved passively.

The first controlled study included 30 acute non-ambulant stroke patients, who either practiced on the system on every workday for four weeks or who were given physiotherapy for 30 min sessions. In addition, both groups were given 30 min normal physiotherapy each workday. The initial conditions of the two groups were comparable. At the end of the study, there was no difference between the groups with respect to restoration of ability to walk or improvement in walking speed (12). Mayr et al. (2007) published a randomized and controlled study with a crossover design with 16 patients. The treatments received by the two groups were A-B-A and B-A-B,

TABLE 1

Prospective randomized studies on Bobath physiotherapy with hemiparetic patients

Authors	n	Therapy	Dependent variables	Results
Lord & Hall, 1986	39	G _{ex1} : Bobath G _{co} : Conventional PT	ADL competence	No difference
Dickstein et al., 1986	131	G _{ex1} : Bobath G _{ex2} : PNF G _{co} : Conventional PT	ADL competence	No difference
Basmajian et al., 1987	29	G _{ex1} : Bobath G _{co} : Behavioral therapy PT	Arm function	No difference
Lincoln et al., 1999	282	G _{ex1} : Bobath G _{ex2} : Bobath + 25 min PT with qualified PT G _{co} : Bobath + 25 min PT with „helpPT“	Arm function, ADL competence	No difference
Langhammer & Stanghelle, 2000	61	G _{ex1} : Bobath G _{co} : MRP	Motor function, ADL competence	Difference in favor of MRP in motor function (p = 0.025), no difference in ADL competence, shorter period in rehabilitation (p = 0.008)
Platz et al., 2005	62	G _{ex1} : ABT + PT G _{ex2} : Bobath + PT G _{co} : PT	Arm function	Difference in favor of AFT (p = 0.04)
Wang et al., 2005	44	G _{ex1} : Bobath G _{co} : Orthopedic PT	Motor function, ADL competence	Difference in favor of Bobath (p = 0.023)
van Vliet et al., 2005	120	G _{ex1} : Bobath G _{co} : MRP	Motor function, ADL competence	No difference

PT, physiotherapy; ADL, activities of daily living; PNF, proprioceptive neuromuscular facilitation; MRP, motor relearning programs; ABT, arm basic training; G_{ex1}, G_{ex2}, experimental groups; G_{co}, control group

BOX

Search Strategy

The search query was restricted to human studies and consists of three queries:

1) Disease: infarct key words were:

cerebrovascular disorders/ brain injuries/ brain injury, chronic stroke/ cva/ poststroke
cerebrovasc*/ cerebral vascular
cerebral/ cerebellar/ brain/ vertebrobasilar
infarct*/ ischaemi*/ thrombo/ embolic/ apoplexy
cerebral/ brain/ subarachnoid
haemorrhage/ hemorrhage/ haematoma/ hematoma/ bleed
hemiplegia/ exp paresis
hemiparesis/ hemiplegic/ brain injuries
gait disorders/ neurologic

2) Mode of therapy Key words were:

physical therapy modalities/ exercise therapy/ motion therapy, continuous passive *exercise/ *exercise test
robotics/ automation/ orthotic devices
body weight/ weight-bearing
(gait/locomot*) AND (train*/ therapy/ rehabilitat*/ re-educat*)
electromechanical/ electro-mechanical/ mechanical/ mechanized/ mechanized/ driven
(body-weight/ body weight/ AND (support*/relief)
robot*/ orthos*/ orthotic/ automat*/ computer aided/ computer assisted
bws/ harness/ treadmill/ exercise*/ fitness train*/ Lokomat/ GaiTrainer/ Kinetron
continuous passive/ cpm AND therap*

3) Outcome parameter: motor function Key words were:

gait/ exp walking/ locomotion
"range of motion, articular"
recovery of function
walk*/ gait/ ambulat*/ mobil*/ locomot*/ balance*/ stride

This search strategy was modified correspondingly for arm/hand rehabilitation. Studies as abstracts were excluded, as were studies on treadmill training and studies which repeated data which had already been published.

where A represents three weeks of treatment with the exoskeleton-based system and B three weeks of physiotherapy (13). Because of the possible carry-over of the effects of one phase into the subsequent phase and in accordance with the recommendations of the Cochrane Collaboration (14), only the first phase, before the first crossover, was considered. At the end of the first phase, there was no significant difference between the two groups. However, at the end of the third phase, there was a significant difference in favor of the A-B-A group.

Hesse and Uhlenbock developed an electromechanical gait trainer (15). This is based on the end effector principle, meaning that the feet are moved, but the proximal joints are free. The patient is fastened with a belt and stands on two foot plates. The movements of these simulate the leg's stand and swing phases. The multicenter German Gait Trainer Study (DEGAS) included 155 non-ambulant acute stroke patients from four clinics (16). The patients' circulation was stable, and they could at least sit on their beds, holding on to the edge. They

were given either 20 min locomotion training on the system and 25 min physiotherapy (group A) or 45 min physiotherapy (group B) each workday for four weeks.

After completing the therapy, significantly more patients in group A could walk independently: 41 of 77 (53%) in group A, in comparison to 17 of 78 (22%) in group B (chi-square test with Bonferroni correction, $p < 0.0001$). The increase in walking speed during the intervention was also significantly greater in the locomotion group (Mann Whitney Test with Bonferroni correction, $p < 0.0001$). The superior walking ability in the locomotion group in comparison to the physiotherapy group was maintained six months later; there were then 54 independently walking patients in group A (70%), in comparison to 28 (36%) in group B ($p < 0.0001$). In contrast, the change in walking speed in the interval from study end to follow-up was no longer significantly different. The DEGAS has examined competency in the activities of daily life with the help of the internationally established Barthel Index (BI). The outcome parameter was a BI of at least 75, which is regarded as the limit for a safe return home. This level was reached by 44 patients in group A (57%) at the end of the intervention, in comparison with only 21 (27%) in group B ($p < 0.0001$).

Tong et al. (Hong Kong) examined 50 acute non-ambulant patients. They were divided into two groups, who were treated for four weeks with either the gait trainer (GT) or with the system and functional electrostimulation (FES) (17). The control group was exclusively given physiotherapy. Walking ability and walking speed were significantly increased in both experimental groups in comparison to the control group. The corresponding p values for the comparison GT vs. conventional therapy were 0.005 and 0.011, respectively. The p values for the comparison GT+FES vs. conventional therapy were 0.002 and 0.001, respectively (Mann Whitney Test). Additional FES could not enhance the effect; there were no differences between the two groups.

Peurela et al. studied chronic patients who could already walk ($n = 45$). These patients were assigned to two experimental groups, with either only training on the system or training together with FES, as well as a control group, who were given intensive walking training. The walking speed and time were improved in all three groups; there were no differences between groups (18).

The potential side-effects of system-supported gait rehabilitation include excessive stress on the joints, particularly with prior arthrosis, and excessive cardiovascular stress on the patients, who often suffer from multiple diseases. The inclusion criteria allowed for this and no relevant side-effects were found in these studies.

Figures 1 and 2 give a descriptive depiction of the results of the five randomized and controlled studies ($n = 298$ patients) for walking ability and walking speed.

Arm/hand rehabilitation

Seven controlled studies were identified (table 3). Pioneer is an end-effector based system from the Massachusetts Institute of Technology (MIT), Boston/USA, with which the patient grasps with his hand a robot arm which can be

TABLE 2

Prospective randomized studies on the robot-supported therapy of the lower extremities of hemi-paretic patients

Authors	Study object	Design	n	Therapy	FAC (0–5) ini median	FAC (0–5) term median	FAC (0–5) follow-up median	Walking speed ini (m/s)	Walking speed term (m/s)	Walking speed follow-up (m/s)
Acute, initially non-ambulant patients										
Tong et al., 2006	Gait trainer GT I	RCS with 3 arms	50	G _{ex1} : 20 x 20 min GT + FES plus 10 min PT G _{ex2} : 20 x 20 min GT plus 10 min PT G _{co} : 20 x 30 min convent. PT	G _{ex1} : 1 (0–1) G _{ex2} : 1 (0–1) G _{co} : 1 (1–2)	G _{ex1} : 4 (1–4) G _{ex2} : 3 (1–3) G _{co} : 2 (1–2) p = 0.001*2	–	G _{ex1} : 0.0±0 G _{ex2} : 0.0±0 G _{co} : 0.0±0	G _{ex1} : 0.63±0.37 G _{ex2} : 0.47±0.21 G _{co} : 0.24±0.3 p = 0.001*2	–
Pohl et al., 2006	Gait trainer GT I	RCS with 2 arms	156	G _{ex} : 20 x 20 min GT plus 25 min PT G _{co} : 20 x 45 min PT	G _{ex} : 1 (0–2) G _{co} : 1 (0–2)	G _{ex} : 4 (2–4) G _{co} : 2 (1–3) p = 0.001*2	G _{ex} : 5 (3–5) G _{co} : 3 (1–4) p = 0.001*2	G _{ex} : 0.13±0.17 G _{co} : 0.14±0.19	G _{ex} : 0.44±0.47 G _{co} : 0.32±0.36 p = 0.001*2	G _{ex} : 0.53±0.31 G _{co} : 0.36±0.42 ns
Husemann et al., 2007	Lokomat	RCS with 2 arms	30	G _{ex} : 20 x 20 min Lokomat plus 20 min PT G _{co} : 20 x 40 min PT	G _{ex} : 0 (1–4) G _{co} : 0 (1–4)	G _{ex} : 1 (1–4) G _{co} : 1 (1–4) n.s.	–	G _{ex} : 0.12±0.02 G _{co} : 0.14±0.03	G _{ex} : 0.20±0.03 G _{co} : 0.20±0.05 ns	–
Mayr et al., 2007	Lokomat	RCS*1 with 2 arms	16	G _{ex} : 15 x 30 min Lokomat G _{co} : 15 x 30 min PT	G _{ex} : 2 (1.5–2) G _{co} : 2 (2–3)	G _{ex} : 3 (3–4) G _{co} : 2.5 (2–3) n.s.	–	G _{ex} : 90s (40–140) G _{co} : 75s (30–200)	G _{ex} : 75s (50–100) G _{co} : 70s (35–70) ns	–
Chronic, moderately affected patients										
Peurala et al., 2005	Gait trainer HGT I	RCS with 3 arms	45	G _{ex1} : 15 x 20 min GT + FES plus 55 min PT G _{ex2} : 15 x 20 min GT plus 55 min PT G _{co} : 15 x 20 min convent. gait training plus 55 min PT	G _{ex1} : 4 (3–4) G _{ex2} : 4 (3–4) G _{co} : 4 (3–4)	–	–	G _{ex1} : 0.23 G _{ex2} : 0.25 G _{co} : 0.25	G _{ex1} : 0.28 G _{ex2} : 0.33 G _{co} : 0.31 ns	–

RCS, randomized controlled study; *1 A-B-A or B-A-B design, only the first phase was considered, to avoid the so-called "carry-over effect"; G_{ex1}, G_{ex2}, experimental groups; G_{co}, control group; GT, gait trainer GT[1]; FES, functional electrostimulation; PT, physiotherapy; *2, significantly greater improvement in the experimental groups; FAC (0–5), functional ambulation category; ns, not significant.

moved in the horizontal plane. This allows practice of the shoulder elbow movement on one side (19). A screen gives targets to be reached and a impedance control simulates the experienced hand of the therapist.

Two controlled studies with a total of 76 severely affected acute stroke patients (stroke less than four weeks before the start of the study) compared 20 or 25 h therapy with the robot (one hour per workday, four or five days in the week) with a placebo therapy, in which the patients operated the robot with the unaffected arm (20, 21). The increase in strength in the shoulder and elbow musculature was significantly greater in the experimental group. In contrast, there were no differences in the strength of distal segments or motor functions.

A bilateral end-effector based system has also been used. Each hand grasps a handle. With the help of two drives, pronation and supination of the lower arm can be practiced, as well as flexion and extension of the wrist, on both sides. This is either passive, or the unaffected hand leads the affected hand. Alternatively, the paretic hand must support the movement. Mode 1 is for purely passive motion; mode 2 is when the unaffected hand leads the affected hand; mode 3 is when the paretic hand

must support the movement. The objective of this bilateral practice is that the paretic side should be facilitated. The distal design allows for the greater cortical representation of the hand.

The first study included 44 acute stroke patients with a paralyzed hand (22). The patients practiced each workday for six weeks, either with the system or with electrostimulation of the hand extensor in addition to conventional rehabilitation. Surface electrodes were used to provide external stimulation to the hand extensor 60 to 80 times per session. EMG triggering was optional. After the end of the intervention and at follow-up, the strength of proximal and distal segments and control of motor functions in the paretic upper extremity was significantly better in the experimental group.

Masiero et al. (Italy) have developed a string robot. This uses the marionette principle to allow the patient to practice three dimensional shoulder elbow movements at a very early stage. A controlled study included 35 patients who had suffered a stroke less than one week previously. A comparison was made between four hours therapy per week for five weeks with the robot vs. placebo therapy of lower intensity, in which the patient moved

FIGURE 1

Robot- and system-supported rehabilitation of walking. Independent walking to the end of the treatment phase. Depiction of the effects in all studies in a Forrest plot. The effects are the chance of being able to walk independently again (odds ratio, OR). If OR>1, this means that there is an increased chance of being able to walk again. RD, risk differences; CI, confidence interval; random, evaluation for random effects; N, number of included patients

the robot with the unaffected arm. The robot group achieved significantly greater increases in motor control and strength of the upper extremity (23).

Chronic patients were examined in randomized controlled studies with three systems.

One of these allows bilateral shoulder-elbow movement with the help of two robot arms. The healthy side leads and the affected extremity follows the facilitating movement. The controlled study included 27 chronic patients, who had either been treated with the robot or with Bobath therapy, each 24 times for 60 min. The robot group significantly improved their motor control and strength during the intervention; subsequently there was no difference (24).

Another instrument is a one dimensional system. This moves the arm back and forth in a track. This means that

the patient must support the movement, and purely passive motion is excluded. 19 moderately affected chronic patients practiced 24 times, either with the system or were given physiotherapy of equal intensity. At the end of the intervention, the patients in the experimental group exhibited greater strength in the upper extremity. Motor functions were not examined (25).

The third system is a passive exoskeleton system with five degrees of freedom. Elastic bands protect the arm from gravity. A study which is currently in progress (26) includes chronic stroke patients with moderate to severe arm paresis. The patients train for eight weeks, either three times per week with the system or practice independently at home. According to preliminary results (n = 23), the arm trainer group achieved a significantly greater increase in the Fugl-Meyer Score.

FIGURE 2

Robot- and system-supported rehabilitation of walking. Walking speed (m/s). Depiction of the effects in all studies in a Forrest plot. The effects reflect the improvement in walking speed (odds ratio, OR). If OR>1, this means that there is a significantly greater increase in walking speed in the experimental group. WMD, weighted mean differences; CI, confidence interval; SD, standard deviation; random, evaluation for random effects; N, number of included patients

TABLE 3

Prospective randomized studies on the robot-supported therapy of the upper extremities of hemi-paretic patients

Authors	Study object	Study design	n	Therapy	FM ini (0–66)	Δ FM (0–66) or FM (0–66) term	Δ FM (0–66) or FM (0–66) follow-up	Increase in muscle strenght term – ini	Increase in muscle strenght follow-up – term
Aisen et al., 1997	MIT Manus	RCS with 2 groups	20 acute	G _{ex} : 20 x 60 min MIT-Manus G _{co} : 20 x 60 min placebo	G _{ex} : 17.1±15.2 G _{co} : 13.8±16.6	G _{ex} : Δ 14.1±9.7 G _{co} : Δ 10.1±11.6 ns	–	p=0.02	–
Volpe et al., 2000	MIT Manus	RCS with 2 groups	56 acute	G _{ex} : 25 x 60 min MIT-Maus G _{co} : 25 x 60 min placebo	G _{ex} : 6.0±2.5 G _{co} : 5.0±1.0	G _{ex} : 12.0±3.0 G _{co} : 10.0±4.0 ns	–	p=0.05	–
Hesse et al., 2005	BI MANU-TRACK	RCS with 2 groups	44 acute	G _{ex} : 30 x 20 min Bi-Manu-Track G _{co} : 30 x 20 min Electro-stimulation	G _{ex} : 7.9±3.4 G _{co} : 7.3±3.3	G _{ex} : 24.6±14.9 G _{co} : 10.4±7.5 p<0.001	G _{ex} : 30.0±16.8 G _{co} : 16.6±14.9 p<0.001	p<0.001	p<0.001
Masiero et al., 2007	NeReBot	RCS with 2 groups	35 acute	G _{ex} : 25 x 50 min NeReBot G _{co} : 25 x 30 min placebo NeReBot	G _{ex} : 8.0 G _{co} : 6.0	G _{ex} : Δ 15.8 G _{co} : Δ 10.3 p<0.05	G _{ex} : Δ 26.0 G _{co} : Δ 16.3 p<0.01	p<0.05	ns
Lum et al., 2002	MIME Robot	RCS with 2 groups	27 chronic	G _{ex} : 24 x 60 min MIME G _{co} : 24 x 60 min Bobath	G _{ex} : 24.8±4.5 G _{co} : 26.6±4.7	G _{ex} : Δ 4.7±0.7 G _{co} : Δ 3.1±0.4 p<0.043	G _{ex} : Δ 4.9±0.8 G _{co} : Δ 4.8±0.7 ns	p<0.02	ns
Kahn et al., 2006	ARM Guide	RCS with 2 groups	19 chronic	G _{ex} : 24 x ARM guide G _{co} : 24 x grasping practices	–	–	–	ns	–
Housman et al., 2007	T-Wrex	RCS with 2 groups	23 chronic	G _{ex} : 24 x 60 min T-Wrex G _{co} : 24 x 60 min own training	G _{ex} : 24.0 ± 7.0 G _{co} : 17.0 ± 5.0 p=0.02	G _{ex} : Δ 3.7 ± 2.3 G _{co} : Δ 2.7 ± 2.7 p<0.01	–	–	–

RCS, randomized controlled study; FM, Fugl-Meyer Assessment Score (0–66); Δ, FM term minus FM ini or FM follow-up minus FM term; ns, not significant, p>0.05; chr., chronic patients, time from stroke >6 months; p, significant difference in favor of the experimental group.

The most important potential side effect in robot therapy of the upper extremities is excessive stress on the joints and tendons. The inclusion criteria and therapy intensities allowed for this and no relevant side effects occurred.

Conclusion

Robot- and system-supported motor rehabilitation opens new perspectives for stroke patients. It intensifies the therapy without placing excessive demands on the therapist. Currently available results appear to justify this development, even though the available data are still sparse. The authors could not perform a pooled meta-analysis on system-supported gait rehabilitation, because of the heterogeneity of the study results. The tendency was for the therapy – particularly end effector-based electromechanical gait trainers – to be linked to a greater probability of being able to walk independently again. Additional studies are therefore urgently necessary. These should include comparisons with established therapies and should cover questions of cost. The therapeutic effect of robot-supported therapy of the upper extremity is currently difficult to evaluate.

None of the studies demonstrated improvements which were relevant to everyday activities. Moreover, some were compared with placebo therapy (20, 21, 23). On the other hand, the systems offer a chance for severely affected arms, which are regarded as being difficult to rehabilitate. Robot-supported therapy is currently experiencing a boom and the slogans are even more "degrees of freedom, telerehabilitation and virtual worlds". If we are to avoid the trap of "over-engineering" – technically overdemanding solutions – close cooperation is essential between doctors and system manufacturers. We must also once again emphasize the inadequate study results and the limited applicability of the results to everyday activities.

The robot will never be able to replace the interpersonal contact between therapist and patient which is so necessary for rehabilitation. It is only an additional option to intensify therapy.

Note

The author can provide the proper names of the systems mentioned in the text

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Conflict of interest statement

Dr. Beate Brandt-Hesse, Berlin, the wife of the first author, holds the national patents for the systems Gangtrainer GT I and Bi-Manu-Track, which she also markets. The other two authors declare that no conflict of interest exists according to the guidelines of the International Committee of Medical Journal Editors.

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