Use of the robot assisted gait therapy in rehabilitation of patients with stroke and spinal cord injury

Article *in* European Journal of Physical and Rehabilitation Medicine · March 2012

Source: PubMed

4 authors:

Patrizio Sale
Ospedale Sant'Isidoro Trescore Balneario (Bg) FERB Onlus

Marco Franceschini
Istituto di Ricovero e Cura a Carattere Scientifico San Raffaele Pisana

Andreas Waldner
Private Hospital Villa Melitta

Stefan Hesse

EUR J PHYS REHABIL MED 2012;48:111-21

Use of the robot assisted gait therapy in rehabilitation of patients with stroke and spinal cord injury

P. SALE [1], M. FRANCESCHINI [1], A. WALDNER [2], S. HESSE [3]

[1]Department of NeuroRehabilitation, IRCCS San Raffaele Pisana, Rome, Italy
[2]Privatklinik Villa Melitta, Neurological Rehabilitation, Bozen, Italy
[3]Medical Park Humboldtmühle Berlin Department Neurological Rehabilitation Charité, University of Medicine, Berlin, Germany

Difficulty in walking is a major feature of neurological disease, and loss of mobility is the activity of daily living on which patients place the greatest value. The impact on patients is enormous, with negative ramifications on their participation in social, vocational, and recreational activities. In current clinical practice the gait restoration with robotic device is an integral part of rehabilitation program. Robot therapy involves the use of a robot exoskeleton device or end-effector device to help the patient retrain motor coordination by performing well-focused and carefully directed repetitive practice. The exoskeleton, as an assistive device, is also an external structural mechanism with joints and links corresponding to those of the human body. These robots use joint trajectories of the entire gait cycle and offer a uniform (more or less) stiff control along this trajectory. In this field the new powered exoskeleton ReWalk (Argo Medical Technologies Ltd) was developed to have an alternative mobility solution to the wheelchair and rehabilitation treatment for individuals with severe walking impairments, enabling them to stand, walk, ascend/descent stairs and more. The end-effector-based robot is a device with footplates placed on a double crank and rocker gear system. Alternatives to powered exoskeletons are devices that use movable footplates to which the patient's feet are attached. All devices include some form of body weight support. Prominent goals in the field include: developing implementable technologies that can be easily used by patients, therapists, and clinicians; enhancing the efficacy of clinician's therapies and increasing the ease of activities in the daily lives of patients.

Key words: Rehabilitation - Stroke - Spinal cord injuries - Robotics - Orthothic devices.

Corresponding author: P. Sale, IRCCS San Raffaele Pisana, Via della Pisana 235, 00163 Rome, Italy.
E-mail: patrizio.sale@gmail.com

Almost 650 million people around the world live with a disability, most of who require ongoing intensive physiotherapy and rehabilitation. The most common neurological causes of debilitation include stroke, Parkinson's disease (PD), cerebral palsy, multiple sclerosis (MS) spinal cord injury (SCI) and traumatic brain injury (TBI), are the main causes of motor disability among adults and are expected to impose an increasing social and economic burden on our country.[1]

Difficulty in walking is a major feature of neurological disease, and loss of mobility is the activity of daily living on which patients place the greatest value.[2] Walking ability, though important for quality of life and participation in social and economic life, can be adversely affected by neurological disorders such as SCI, stroke or TBI.[3] The impact of these pathologies on patients is enormous, with negative ramifications on their participation in social, vocational, and recreational activities. The neurological field mostly aims to help restore muscle control or to help foster muscle control in those born with little or none.

Musculoskeletal therapy assists in strengthening and restoring functionality in the muscle groups and the skeleton, and in improving coordination. The recovery of gait for all patients with impairments of the central nervous system (CNS), *e.g.* stroke, SCI and TBI is an integral part of rehabilitation and often influences whether a patient can return home or to work.[4] In 2009 the National Institute of Neurological Disorders and Stroke reported that stroke is the third leading cause of death in the United States and the other developed world countries. It is the primary cause of long-term disability in these countries. Concerning its risk factors, it has been shown that aging is the most important independent risk factor for stroke.[5] For the decades after the age of 55, the stroke rate doubles.[5] Also it is estimated that in the EU, the proportion of the population aged over 65 will rise from 17.1% in 2008 to 30% in 2060 and that the proportion of persons aged over 80 will rise from 4.4% to 12.1% over the same period (EUROSTAT population projections). Neurological conditions, especially stroke, are a major cause of mortality and disability among these older populations, whilst worryingly becoming more common in people of working age below 65 years.[6, 7] Demographic changes with remarkable aging of the general population will aggravate this problem, since the relative incidence of stroke doubles for every decade after 55 years of age. Incidence of a first stroke in Europe is about 1.1 million and prevalence about 6 million. 75% of stroke sufferers survive for at least one year. Many individuals affected by a neurological impairment fail to recover the functional use of the lower limbs, even after a prolonged rehabilitative treatment: these functional limitations are responsible for the reduction in the quality of life.[8] Furthermore, more than 50% of all stroke events occur in patients older than 75 years.[5] In addition, there is a higher prevalence of stroke in men than in women: the stroke incidence was about 30% higher in men than in women. After a stroke the muscle weakness, the muscle tonus, the balance and the cardiovascular condition contribute to decreasing walking velocity and endurance, and finally increase the disability.[9, 10] Lower extremity strengthening exercises and task-specific training can be used to recovery walking ability in individuals' post-stroke.[11-13]

In current clinical practice the gait restoration with robotic device is an integral part of rehabilitation program of brain-impaired patients.

A "rehabilitation machine" is a mechatronic or robotic system able to support the therapist during the administration of programmable and customized rehabilitation programs.

It is composed by a mechanical structure where the following modules are present: 1) actuators; 2) energy supply; 3) proprioceptive and exteroceptive sensors, providing information on the machine status and the interaction between the machine and the environment, respectively; 4) a microcontroller, dedicated to the processing of data from sensors and generation of motor control commands; and 5) a human machine interface (graphical user interface), dedicated to user inputs, data recording and feedback output.

For mobility-impaired patients, gait retraining is an integral part of the rehabilitation treatment.[14] Neurologic motor rehabilitation is directed toward the re-learning of motor skills. Rehabilitation robotics is a special branch of robotics, which focuses on machines that can be used to help people recover from severe physical trauma. A specific focus on biomedical engineering can also be considered, as well as human-robot interaction. In this field, clinicians, physio-therapists, and engineers collaborate in helping to rehabilitate patients.[15] Different modalities of gait rehabilitation are used in neurological lower limb rehabilitation, such as manually assisted over-ground training and manually assisted treadmill training with or without the body weight support (BWS). Robotic devices have been developed to relieve physical therapists from the strenuous and not ergonomic burden of manual BWS.[16, 17] Technological innovations provided an opportunity to design interventions that take many key aspects for stimulation of motor relearning.[18] For gait training it is then of the most critical importance to walk repetitively in a natural gait similar to over-ground gait [19, 20] and with the correct proprioceptive and exteroceptive feedback.[21]

Though rehabilitation robotics has applications in all three areas of physical therapy, most of the work and development is focused on musculoskeletal uses of robotics.

Recently the applications within the neurological field have been increasing with the advancements in robotic prosthesis. Prominent goals in the field include: developing implementable technologies that can be easily used by patients, therapists, and clinicians; enhancing the efficacy of clinician's therapies; and increasing the ease of activities in the daily lives of patients.

Robot Assisted Gait Therapy (RAGT) involves the use of a robot orthotic device to help the patient retrain motor coordination by performing well-focused and carefully directed repetitive practice.[22, 23] The history of robot-assisted training started with the adaptation of industrial robotic manipulators to the field of rehabilitation.[24] The field of robot assisted treadmill training has evolved significantly during the last ten years, and the robotic devices can be divided into exoskeletons and end effector-based systems device. The first research on rehabilitation robotics dates back 1960s, in particular on development of technologies to augment the abilities of able-bodied humans, which often focused on military applications. In particular early research in powered human exoskeleton devices began in the late 1960s, almost in parallel between a number of research groups in the United States and in the former Yugoslavia.[25] Furthermore, the history of rehabilitation engineering can be traced back to the development of functional prosthesis. Functional prosthesis can be considered the backbone of rehabilitation robotics. The exoskeleton research in the United States can be traced back to 1965, when the US Department and General Electric developed HARDIMAN.[26]

Exoskeletons devices

The exoskeleton, as an assistive device, is an external structural mechanism with joints and links corresponding to those of the human body. Most exoskeleton robots that are currently being developed focus on the support of the entire gait cycle as a single unit.[27, 28] These robots use joint trajectories of the entire gait cycle and offer a uniform stiff control along this trajectory. This means that the patient receives support in gait phases where support is necessary but also in phases where support is not necessary.

A powered exoskeleton is a powered mobile machine consisting primarily of an exoskeleton-like framework worn by a person and a power supply that supplies at least part of the activation-energy for limb movement. The human wears the exoskeleton, and its actuators generate torques applied on the human joints. In utilizing the exoskeleton as a human power amplifier, the human provides control signals for the exoskeleton, while the exoskeleton actuators provide most of the power necessary for task performance. The human becomes part of the system and applies a scaled-down force in comparison with the load carried by the exoskeleton.

The first exoskeleton was co-developed by General Electric and the United States military in the 1960s, and was named Hardiman (and which made lifting 250 pounds [110 kg] feel like lifting 10 pounds [4.5 kg]). It was impractical due to its 1,500 pound (680 kg) weight (26). The project was not successful. Every attempt to use the full exoskeleton resulted in a violent uncontrolled motion, and as a result it was never tested with a human inside. Exoskeletons could also be regarded as wearable robots: a wearable robot is a mechatronic system that was designed around the shape and function of the human body, with segments and joints corresponding to those of the person externally coupled with.

Increasing recognition from the scientific community means that this technology is now employed in tele-manipulation, human-amplification, neuromotor control research and rehabilitation, and to assist with impaired human motor control. In clinical rehabilitation practice the robotic exoskeletons were conceived as an aid to mobility and are designed to be used in numerous environments (indoor and outdoor). Depending on the type of interface or adjustment system to the limb, a unilateral or bilateral structure can be used. The configuration adopted consisted of an exoskeleton that included knee and ankle joints, lateral bars joined to the thigh (proximal), the leg (distal) and the foot (support and insole inserted into the shoe), and four securing bands to the limb. An advantage of an exoskeleton is that it moves in parallel with the skeleton of the patient, so that no additional degrees of freedom are needed to follow patient motions.[29]

Lower-limb orthoses, as the most common traditional solution to compensate for disorders related to lower-limb muscular weakness affecting the ankle and knees, are the unilateral knee, ankle and foot orthoses. Also the prosthesis, a device that substitutes for a missing part can be used in rehabilitation treatment. Commercially partial solutions that are available which permit knee flexion during the swing phase but have completely restricted movement (a hollow shell and self-carrying) during the stance phase of a limb can be used in conjunction with a treadmill. Studies carried out on an exoskeleton that propose adaptive control methods which minimize the interaction forces with the patient with respect to an adaptable reference pattern, but these still control the entire gait cycle.[30]

Studies have also shown that walking with the current Lokomat™ frame requires significantly less energy than normal walking.[31] This means that patients are not walking as actively as possible but are able to walk a greater distance. The first and the most used exoskeleton's lower limb robot is the Lokomat™ (Hocoma SA, Switzerland).

The device is a motor-driven gait orthosis secured to a patient's legs while the patient him/herself is supported by a BWS system over a motorized treadmill.[32]

This driven (motorized) gait orthosis (DGO) is a computer-controlled, exoskeletal device wich generates passively guided, symmetrical lower-extremity trajectories that are consistent with a normal physiological gait pattern. The DGO was attached to the treadmill/support frame with a 4-bar linkage and a spring-loaded counterweight system, which provided vertical support and unweighting of the exoskeletal device.[33] The DGO provided trajectory-controlled, guided assistance of the hip and knee joints in the sagittal plane during both stance and swing phases of gait, with non-actuated ankle support.[34] Furthermore, only sagittal motions of the legs are allowed, whereas the pelvis/trunk of the patient is fixated.[35] Hidler showed that in a healthy subject sagittal plane joint moments were found to be quite different, whereas during robot exoskeleton walking trials, subjects demonstrated fewer dorsiflexor moments, fewer knee extensor moments, and greater hip extensor moments. Joint powers in the sagittal plane were found to be similar at the ankle but quite different at the knee and hip joints. Also differences in muscle activity (muscle activation patterns, joint moments and joint powers) were observed between the two walking modalities (active or passive), particularly in the tibialis anterior throughout stance, and in the hamstrings, vastus medialis and adductor longus during swing.[36]

The other commercial device the "AutoAmbulator" (Motorica, Israel) is a rehabilitation device designed to help patients get back on their feet after suffering strokes or other debilitating injuries and consisting of a treadmill, an overhead lift, a pair of articulated arms, and 2 upright structures housing the computer controls and parts of the mechanism.[37] The patients are attached to the overhead lift and raised to a standing position over the treadmill where weight-bearing can be assessed. The articulated robot arms mounted to the upright structures are hinged outward and are mechanically driven for vertical adjustment.

The gait drive components are computer-controlled through position, time, and distance to provide a smooth, accurate, and coordinated movement of the legs and treadmill through variable speeds. The robot arms move with 4 degrees of freedom corresponding to hip flexion/extension and knee flexion/extension bilaterally. The robot arms provide assistance in the sagittal plane only. The device produces symmetrical reciprocal gait by providing forces throughout the entire gait cycle, including swing phase.[38]

The LOPES project (LOwer-extremity Powered ExoSkeleton) is to design and implement a gait rehabilitation robot for treadmill training. The target group consists of people who have suffered a stroke and have impaired motor control. In particular the LOPES exoskeleton robot is a device which is attached in parallel to the lower limb segments and moves in unison with the patient.[39] The main goals of LOPES were: reduction of the physical load on the therapist/patient, more efficient gait training for stroke patients and selective support of gait functions. Different from other common orthoses, LOPES's exoskeleton is connected to the fixed world, at pelvis height. This makes it possible to compensate for the weight of LOPES, and to apply external corrective joint torques or forces to the patient's pelvis.[40]

The mechanical construction should offer assistance in leg movements in the forward direction and in keeping lateral balance. Compared to other exoskeletons developed for gait training, LOPES has more actuated degrees of freedom, supports a larger range of impedances so that both unhindered walking (patient in charge mode) as fully passive walking (robot in charge mode) is possible. Within the LOPES project, it has been decided to realize this by connecting the limbs of the patient to an exoskeleton so that robot and patient move in parallel.

The ALEX exoskeleton robot was developed for stroke survivors using active leg exoskeleton (ALEX) and a force-field controller, which uses assist-as-needed paradigm for rehabilitation.[41] In this paradigm undesirable gait motion is resisted and assistance is provided towards desired motion. The ALEX II anthropomorphic exoskeleton is intended for gait rehabilitation of patients who have experienced a stroke or spinal cord injury, or who are afflicted with cerebral palsy or spina bifida. The device can be attached to a user's right or left leg while the user walks on a treadmill, in addition to braces that attach to the user's trunk, thigh, and shank.

ALEX II is also enabled with one or more degrees of freedom at the trunk, hip, knee, and ankle, including powered flexion/extension at the hip and knee. The device's control architecture allows a user to learn new gait patterns using force-field controllers that assist or resist the user's movements as needed. The force-field controller achieves this paradigm by effectively applying forces at the ankle of the subject through actuators on the hip and knee joints (41).

The ARTHUS (Ambulation-assisting robotic tool for human rehabilitation) is a device developed to mechanically interact with a single leg during treadmill training. It consists of two moving coil brushless servo motors that drive either end of a two bar linkage. In particular it provides motions to knee and ankle joints in sagittal plane and can generate substantial force required for gait training purpose.[42] Also the robot, provides high-bandwidth force control at one attachment point in the parasagittal plane (*i.e.*, bottom of foot, lower shank, or knee). A recent robotic device for the ankle joint has been developed to address the problem of drop foot that occurs during hemiparetic gait.[43, 44]

The device is a backdriveable or low end-point impedance device that allows mobility at the ankle joint in all three degrees of freedom (DOFs) but actuates the ankle in only two of those three DOFs, namely dorsi/plantarflexion and inversion/eversion. The ankle-bot weighs 3.6 Kg and has low static friction (<1 N-m). It is mounted proximally to the leg and anterior to the shank to minimize perception of loading.[44]

In particular the hybrid assistive limb (also known as HAL) is a powered exoskeleton suit currently in development by Tsukuba University in Japan. It has been designed to expand and improve physical capability of users, particularly people with physical disabilities. There are currently two prototypes: HAL 3, which has bulkier servo-motors and only has the leg function, and HAL 5, which is a full-body exoskeleton for the arms, legs, and torso. HAL 5 is currently capable of allowing the operator to lift and carry about five times as much weight as he or she could lift and carry unaided.

In the last time the new exoskeleton ReWalk (Argo Medical Technologies Ltd) was developed to have an alternative mobility solution to the wheelchair and rehabilitation treatment for individuals with severe walking impairments, enabling them to stand, walk, ascend/descent stairs and more.

ReWalk is a new realization of the powered exoskeleton concept and provides user-initiated mobility; it consists of a light wearable brace support suit, which integrates actuation motors at the joints, an array of motion sensors, a computer system based on sophisticated control and safety algorithms and tailored rechargeable batteries. **Re**Walk enables people with lower limb disabilities such as SCI and Spina Bifida to carry out routine ambulatory functions.[45]

End-effector devices

The end-effector-based robot is a device with footplates placed on a double crank and rocker gear system. Alternatives to powered exoskeletons are RAGT devices that use movable footplates to which the patient's feet are attached. All devices include some form of body weight support.

The first end-effector robot for gait training rehabilitation was the Gait Trainer (Reha-Stim Berlin).[46] This device is a robot-assisted gait trainer with a system of body-weight support. In particular the device applies the principle of movable footplates, where each of the patient's feet is positioned on a separate footplate whose movements are controlled by a planetary gear system, simulating foot motion during stance and swing. The foot plates were motor driven and control 3 DoF (?) of the foot within the sagittal plane.

A planetary gear provides correct repartition of stance and swing phase [60:40].[46] Step length and cadence could be set individually and the patient's knees are not fixed, in order to allow the therapists access for physical contact with the patient and also allows him to do minor corrections of the knee motion if needed.[47] A good characteristic of this device is a possibility to use the Functional Electrical Stimulation during the exercises and the possibility to have the manual assistance from the physiotherapist in real time.

A limitation of the gait trainer is that the only interaction takes place on the foot sole so that typical poor joint stability of stroke patients cannot be controlled and it is not possible to deviate from the prescribed trajectory in space.[48] Other limitations are the incomplete unloading of the lower limb in the swing phase of gait.

The mechanical gait device LokoHelp (LokoHelp Group Germany) is a combined end-effector based device system fixed onto the band of a motor-driven treadmill, used in combination with a BWS harness, that transmits the treadmill movement to levers that induce the stance and swing phases. The main technical characteristic was that the device is designed to be placed on a treadmill and can easily be installed and removed and the patient is able to practice on a fixed trajectory.[49]

The other end-effector based robot device HapticWalker is based on the principle of programmable footplates and trajectories. In particular on such a machine, the footplates are mounted on the end effectors of two separate robot arms. It is the first gait rehabilitation device which is not restricted to training of walking on even ground.[50] The system comprises two 3 DOF robot modules, moving each foot in the sagittal plane. Foot movement along the two base axes in this plane (horizontal, vertical) is performed by linear direct drive motors, which move independently on a common rail, but are connected via a slider-crank system.

The HapticWalker comprises a translatory and rotatory footplate workspace needed for permanent foot attachment along arbitrary walking trajectories during all phases of gait. The HapticWalker footplate dynamics were designed so that not only smooth foot motions at moderate walking speeds can be accomplished, but also the realistic simulation of walking speeds of up to 5 km/h with a maximum acceleration of 3.5 g and 120 steps/min.[51]

The foot module contains a 6 DOF force/torque sensor and the footplate. Each robot is based on a modular machine design where the current foot module can be substituted by a further 3 DOF module gaining 6 DOF at each footplate, thus enabling free foot movement in 3D space (the foot plates allow practice of floor walking, stair climbing and stair descending).[52]

The currently commercially available gait machines Lokomat, AutoAmbulator, LokoHelp and GT I are limited to the repetitive exercise of walking on the floor but stair climbing up and down, is an essential part of everyday mobility, and a main goal of a rehabilitation treatment. The Haptic Walker robot was the first device to additionally enable harness-secured patients the repetitive practice of climbing up and down stairs without overstressing therapists.[53] The dimensions and the required high voltage during natural gait of healthy subjects limited its clinical utility.[50]

The latest innovation in end effector machines is the G-EO System rehabilitation robot (Reha Technologies, Italy).[54] The footplates had 3 DoF each, consenting the control of the length and the height of the steps and the foot plate angles. The maximum step length corresponded to 550 mm, the maximum achievable height of the steps was 400 mm, the maximum angles were ±90°. The maximum speed of the footplates was 2.3 km/h.[54] It is not combined with a treadmill.

Spinal Cord and RAGT

Body-weight-supported treadmill training (BWSTT) were a first "robotic" rehabilitation intervention used to promote the recovery of walking in individuals with motor-incomplete SCI.[55] More than two decades ago it was observed that it was possible to induce locomotor movements in SCI cats over a treadmill with partial BWS [56] and the training improved this ability.[57]

The first study on SCI patients and RAGT were conduct on 2001 from Colombo *et al.*[58] Similarly most recently it was confirmed that locomotor movements could be evoked and trained in persons with incomplete SCI over a treadmill using a partial BWS;[59] patients showed a significant increase of electromyographic (EMG) activity of the lower limbs extensor muscles during the training, thus improving the walking function.[60] Even in complete SCI subjects it could induce a locomotor pattern and increase the extensor muscles EMG activity with the training,[61] but without a corresponding functional improvement.

In Gorassini's papers on people with chronic SCI, increases in tibialis anterior and hamstring muscle activity during treadmill locomotion were associated with improved ambulatory capacity following BWS.[62] Also the BWS training can improve the autonomic regulation of heart rate (HR) and blood pressure (BP) and has a positive effect on vascular dynamics.[63] Comparison of RAGT with manually assisted treadmill training has shown that muscular activity in patients and healthy controls were reduced when walking with a robotic device.[64, 65]

In the last five years in order to overcome the limitations of traditional physiotherapeutic treatments in SCI, robotic devices for rehabilitation have been used on small number of patients: they are able to provide a safe and intensive motor therapy to patients with mild, moderate and severe lower limb motor impairment.[66-69] These are the first attempts to use the robotic devices in SCI. Unfortunately techniques for selecting important training parameters, such as walking speed and body-weight support, have not been established.[70]

Robotic devices with body-weight-support have developed to assist leg movements and ensure adequate foot clearance during the swing phase in patients with SCI.[71, 72] Lam investigated the muscle activity in nine ambulatory patients with incomplete spinal cord injuries during rehabilitation treatment by Lokomat robotic gait orthosis.[73] The Lokomat robot is also used for Isometric force measurements in the lower extremity of subjects with neurological movement disorders (NMD) because the walking ability has been shown to be related to muscle strength. The muscle strength measurements can be used in SCI to monitor and control the effects of training programs.[74]

In a recent review the quality of current evidence was assed as to the effectiveness of robot-assisted gait training in spinal cord injured patients, focusing on walking ability and performance, but no evidence that robot-assisted gait training improves walking function more than other locomotor training strategies were found.[75, 76] In particular Swinnen showed that the limited number of studies in combination with the small number of patients treated and the fairly low methodological scores, demonstrate the low level of evidence currently available with regard to the effectiveness of robot-assisted gait training in persons with SCI.[77]

Stroke and RAGT

The rationale for the use of RAGT is related to the evidence that stroke causes a partial destruction of the cortical tissue and results in a disturbed generation of motor programs through the involvement of sensorimotor areas too. Also robot-mediated sensorimotor training and task-oriented repetitive movements can improve muscle strength and movement coordination in patients with neurological impairment.[78, 79]

The introduction of RAGT systems is said to have the following advantages: a reduced number of rehabilitation staff needed to assist the patient in gait training;[80] normally, 2-3 of the staff are needed to support the body weight of the patient, while also assisting the patient's leg movements and there is also a non-trivial risk of injury to the human trainers during physiotherapy.[81] Hidler reports that as therapists become tired during the session, the patient has to adjust to the changing assistance of the physiotherapist in addition to their impairment.[82]

Task-oriented repetitive movements could improve muscular strength and movement coordination in patients with impairments due to neurological disorder that leads to motor control abnormalities, weakness and spasticity.[83] High-intensity and task-specific robot therapeutic interventions consisting of active, highly repetitive movements, as provided by robot-mediated therapy, had led to significant improvements in the cortical reorganization and motor function in disabled people, more than one year after the onset of stroke.[84] With such a device, the required amount of support to limb and foot movements can be provided, thereby allowing active practice of movements when this is not possible otherwise. This increases the potential to train intensively, with active contribution by the patient to functional exercises.

The domain of application, rehabilitation of stroke, has seen an increasing number of studies investigating use or robotic and virtual reality tools in support of delivering rehabilitative treatment more frequently.[85, 86] Although many studies support the argument in favour of advantages gained by robot-mediated therapies, integration of these technologies into everyday clinical practice and for home use has been very slow. The application of lower limb rehabilitation robotics has been shown to be effective.[87, 88] However, transfer of robotic training effects to activities in daily life is limited, as is observed for most interventions in stroke rehabilitation, including conventional therapy.[89] This post-stroke therapy is labour-intensive, usually relying on one-on-one interactions with a trained therapist.

Although standardized evaluations are available, patient progress is often evaluated subjectively, with the therapist making hands-on or visual judgments about a patient's isolated motor control or functional use of the affected limb. Different reviews show that robot-mediated sensorimotor training and task-oriented repetitive movements can improve muscle strength and movement coordination in patients with neurological impairment.[90, 91] Randomized controlled trials have shown the effectiveness of RAGT and promising effects on functional and motor outcomes in patients after stroke.[92, 93] Pohl *et al.* conducted a randomized controlled trial. It investigated the effect of repetitive locomotor training on an electromechanical gait trainer (gait trainer GT I) plus physiotherapy in subacute stroke patients (N.=155) and showed that Intensive locomotor training plus physiotherapy resulted in a significantly better gait ability and daily living competence in subacute stroke patients compared to physiotherapy alone.[48]

A Cochrane Report that includes results observed in trials with two devices, the Gait Trainer I and the Lokomat, has reported that there is evidence to suggest electromechanical gait training may improve independent walking.[94] A recent update published in 2010 of this Cochrane was published in order to justify the large equipment and cost in human resources needed to implement electromechanical-assistive gait devices as well as to confirm the safety and acceptance of this method of training.[95]

In this Cochrane study the author's review provides evidence that the use of electromechanical-assisted gait training devices in combination with physiotherapy increases the chance of regaining independent walking ability for patients after stroke. It appears that patients in the acute and subacute phase after stroke profit more than patients treated more than three months post-stroke.[96]

Further, Geroin *et al.* showed that robot-assisted gait training combined with transcranial anodal direct current stimulation has no additional effect on robot-assisted gait training in patients with chronic stroke but robot-assisted gait training again proved more effective than conventional training in enhancing walking ability in patients with chronic stroke.[96]

Conclusions

Many authors have shown the efficacy of gait training with robotic assistance on improving walking function in a variety of neurological diagnoses but the process aimed at restoring walking function in patients with neurological pathology is challenged by the complexity and variability inherent to these disorders.

Our experience and various articles examined showed that RAGT provides versatile control approaches as a framework to the design of optimal rehabilitation interventions and experimental motor control studies, but the high cost of robot devices raises the question of efficiency in comparison with other training strategies.

It is unclear if the cost differences for the treatment of each patient would favor robot-assisted treatment compared with more conventional therapies for patients with neurological diseases with a moderate to severe lower-extremity impairment. Only one paper analyses these crucial aspects in upper limb robot rehabilitation in stroke patients.[97] Future clinical evaluation should be conducted to compare the effects of robot-aided training *versus* non robot-aided training and manual BWSTT in a long term randomized clinical trial.

References

1. Sale P, Zampolini M, Juocevicius A, Lains JM, Giustini A, Negrini S *et al*. The role of the European physiatrist in traumatic brain injury. Am J Phys Med Rehabil 2011;90:83-6.
2. Robinson CA, Shumway-Cook A, Ciol MA, Kartin D. Participation in Community Walking Following Stroke: Subjective Versus Objective Measures and the Impact of Personal Factors. Phys Ther 2011;91:1865-76.
3. Finlayson ML, Peterson EW. Falls, aging, and disability. Phys Med Rehabil Clin N Am 2010;21:357-73.
4. Schmidt H, Werner C, Bernhardt R, Hesse S, Krüger J. Gait rehabilitation machines based on programmable footplates. J Neuroeng Rehabil 2007;4:2.
5. van Wijk I, Kappelle LJ, van Gijn J, Koudstaal PJ, Franke CL, Vermeulen M *et al*. LiLAC study group. Long-term survival and vascular event risk after transient ischaemic attack or minor ischaemic stroke: a cohort study. Lancet 2005 Jun 18-24;365:2098-104.
6. Van de Port IG, Kwakkel G, van Wijk I and Lindeman E. Susceptibility to deterioration of mobility long-term after stroke: a prospective cohort study. Stroke 2006; 37:167-71.
7. Hoffmann T, Bennett S, Koh C, McKenna K. The Cochrane review of occupational therapy for cognitive impairment in stroke patients. Eur J Phys Rehabil Med 2011;47:513-9.
8. Nichols-Larsen DS, Clark PC, Zeringue A, Greenspan A, Blanton S. Factors influencing stroke survivors' quality of life during subacute recovery. Stroke 2005;36:1480-4.
9. Perry J, Garrett M, Gronley JK, Mulroy SJ. Classification of walking handicap in the stroke population. Stroke 1995;26: 982-9.
10. Mulroy S, Gronley J, Weiss W, Newsam C, Perry J. Use of cluster analysis for gait pattern classification of patients in the

early and late recovery phases following stroke. Gait Posture 2003;18:114-25.
11. Teixeira-Salmela LF, Olney SJ, Nadeau S, Brouwer B. Muscle strengthening and physical conditioning to reduce impairment and disability in chronic stroke survivors. Arch Phys Med Rehabil 1999;80:1211-8.
12. Sullivan KJ, Knowlton BJ, Dobkin BH. Step training with body weight support: effect of treadmill speed and practice paradigms on poststroke locomotor recovery. Arch Phys Med Rehabil 2002;83:683-91.
13. Patton JL, Mussa-Ivaldi FA. Robot-assisted adaptive training: custom force fields for teaching movement patterns. IEEE Trans Biomed Eng 2004;51:636-46.
14. Smania N, Gambarin M, Paolucci S, Girardi P, Bortolami M, Fiaschi A *et al.* Active ankle dorsiflexion and the Mingazzini manoeuvre: two clinical bedside tests related to prognosis of postural transferring, standing and walking ability in patients with stroke. Eur J Phys Rehabil Med 2011;47:435-40.
15. Semprini R, Sale P, Foti C, Fini M, Franceschini M. Gait impairment in neurological disorders: a new technological approach. Funct Neurol 2009;24:179-83.
16. Winchester P, Querry R: Robotic orthoses for body weight-supported treadmill training. Physical medicine and rehabilitation clinics of North America 2006;17:159-72.
17. Volpe BT, Krebs HI, Hogan N. Is robot-aided sensorimotor training in stroke rehabilitation a realistic option? Curr Opin Neurol 2001;14:745-52.
18. Hussain S, Xie SQ, Liu G. Robot assisted treadmill training: mechanisms and training strategies. Med Eng Phys 2011;33:527-33.
19. H. Barbeau, "Locomotor training in neurorehabilitation: emerging rehabilitation concepts," Neurorehabil Neural Repair, vol. 17, pp. 3-11; 2003. V.
20. Dobkin BH. Strategies for stroke rehabilitation. Lancet Neurol 2004;3:528-36.
21. Barbeau H. Locomotor training in neurorehabilitation: emerging rehabilitation concepts. Neurorehabil Neural Repair 2003;17:3-11.
22. Duysens DJ. Significance of load receptor input during locomotion: a review. Gait Posture 2000;11:102-10.
23. Hesse S. Treadmill training with partial body weight support after stroke: a review NeuroRehabilitation 2008;23:55-65.
24. Hogan N. Guest editorial: rehabilitation applications of robotic technology. J Rehabil Res Develop 2000;37.
25. Dollar AM, Herr H. Lower extremity exoskeletons and active orthoses: challenges and state-of-the-art. IEEE transactions on robotics: a publication of the IEEE Robotics and Automation Society 2008;24.1:1-15.
26. Bogue R. Exoskeletons and robotic prosthetics: a review of recent developments. Industrial robot: an international journal 2009;36:421-7.
27. Colombo G. Treadmill training of paraplegic patients using a robotic orthosis. J Rehabil Res Develop 2000;37:693-700.
28. Schmidt H. Development of a robotic walking simulator for gait rehabilitation. Biomedizinische Technik 2003;48:281-6.
29. van der Kooij H, Veneman J, Ekkelenkamp R. Design of a compliantly actuated exoskeleton for an impedance controlled gait trainer robot. Proceedings of the 28th IEEE EMBS Annual International Conference New York City, USA, Aug 30-Sept 3, 2006.
30. Jezernik S, Colombo G, Morari M. Automatic gait-pattern adaptation algorithms for rehabilitation with a 4-DOF robotic orthosis. Robotics and Automation, IEEE Transactions on 2004;20:574.
31. Krewer FM, Husemann B, Heller S, Quintern J, Koenig E. Energy expenditure of hemiparetic patients and healthy subjects: walking in a lokomat vs. on a treadmill. in Evidence-Based Medicine in Neurorehabilitation 2004. Zürich.
32. Colombo G, Joerg M, Schreier R, Dietz V. Treadmill training of paraplegic patients using a robotic orthosis. J Rehabil Res Dev 2000;37:693-700.
33. Hornby TG, Zemon DH, Campbell D. Robotic-assisted, bodyweight-supported treadmill training in individuals following motor incomplete spinal cord injury. Phys Ther 2005;85:52-66.
34. Lünenburger L, Colombo G, Riener R, Dietz V. Biofeedback in gait training with the robotic orthosis Lokomat. Conf Proc IEEE Eng Med Biol Soc 2004;7:4888-91.
35. Hidler JM, Wall AE. Alterations in muscle activation patterns during robotic-assisted walking. Clin Biomech (Bristol, Avon) 2005;20:184-93.
36. Hidler JM, Carroll M, Federovich EH. Strength and coordination in the paretic leg of individuals following acute stroke. IEEE Trans Neural Syst Rehabil Eng 2007;15:526-34.
37. Mantone J. Getting a leg up? Rehab patients get an assist from devices such as HealthSouth's AutoAmbulator, but the robots' clinical benefits are still in doubt. Modern Healthcare (MOD HEALTHC) 2006;13:58-60.
38. West RG, inventor; HealthSouth Corporation, assignee. Powered gait orthosis and method of utilizing same. US patent 6689075. February 10, 2004.
39. Veneman JF, Kruidhof R, Hekman EE, Ekkelenkamp R, Van Asseldonk EH, van der Kooij H. Design and evaluation of the LOPES exoskeleton robot for interactive gait rehabilitation. IEEE Trans Neural Syst Rehabil Eng 2007;15:379-86.
40. Proceedings of the 28th IEEE EMBS Annual International Conference New York City, USA, Aug 30-Sept 3, 2006.
41. Banala SK, Kim SH, Agrawal SK, Scholz JP. Robot assisted gait training with active leg exoskeleton (ALEX). IEEE Trans Neural Syst Rehabil Eng 2009;17:2-8.
42. Emken JL, Wynne JH, Harkema SJ, Reinkensmeyer DJ. A robotic device for manipulating human stepping. IEEE Transactions on Robotics 2006;22:185-9.
43. Roy A, Krebs HI, Williams DJ, Bever CT, Forrester LW, Macko RM *et al.* Robot-aided neurorehabilitation: a novel robot for ankle rehabilitation. IEEE Transactions on Robotics 2009;25.
44. Khanna I, Roy A, Rodgers MM, Krebs HI, Macko RM, Forrester LW. Effects of unilateral robotic limb loading on gait characteristics in subjects with chronic stroke. J Neuroeng Rehabil 2010;7:23.
45. ARGO Medical Technologies Ltd [Internet]. Available from http://www.argomedtec.com/ [cited 2012, Feb 6].
46. Hesse S, Werner C, Uhlenbrock D, von Frankenberg S, Bardeleben A, Brandl-Hesse B. An electromechanical gait trainer for restoration of gait in hemiparetic stroke patients: preliminary results. Neurorehabil Neural Repair 2001;15:39-50.
47. Werner C, Von Frankenberg S, Treig T, Konrad M, Hesse S. Treadmill training with partial body weight support and an electromechanical gait trainer for restoration of gait in subacute stroke patients: a randomized crossover study. Stroke 2002;33:2895-901.
48. Pohl M, Werner C, Holzgraefe M, Kroczek G, Mehrholz J, Wingendorf I *et al.* Repetitive locomotor training and physiotherapy improve walking and basic activities of daily living after stroke: a single-blind, randomized multicentre trial (DEutsche GAngtrainerStudie, DEGAS). Clin Rehabil 2007;21:17-27.
49. Freivogel S, Mehrholz J, Husak-Sotomayor T, Schmalohr D. Gait training with the newly developed 'LokoHelp'-system is feasible for non-ambulatory patients after stroke, spinal cord and brain injury. A feasibility study. Brain Inj 2008;22:625-32.
50. H. Schmidt, D. Sorowka, S. Hesse, and R. Bernhardt, Development of a robotic walking simulator for gait rehabilitation. Biomed Tech (Berl) 2003;48:281-6.
51. Schmidt H, Werner C, Bernhardt R, Hesse S, Krüger J. Gait rehabilitation machines based on programmable footplates. J Neuroeng Rehabil 2007;4:2.

52. Schmidt H, Hesse S, Bernhardt R, Krüger J. HapticWalker – A novel Haptic Foot Device. ACM Transactions on Applied Perception 2005;2:166-80.
53. Schmidt H, Werner C, Bernhardt R, Hesse S, Krüger J. Gait rehabilitation machines based on programmable footplates. J Neuroeng Rehabil 2007 Feb 9;4:2.
54. Hesse S, Waldner A, Tomelleri C. Innovative gait robot for the repetitive practice of floor walking and stair climbing up and down in stroke patients. J Neuroeng Rehabil 2010;7:30.
55. Barbeau H, Fung J. The role of rehabilitation in the recovery of walking in the neurological population. Curr Opin Neurol 2001;14:735-40.
56. Grillner S, McClellan A, Perret C. Entrainment of the spinal pattern generators for swimming by mechano-sensitive elements in the lamprey spinal cord in vitro. Brain Res 1981;217:380.
57. Barbeau H, Julien C, Rossignol S. The effects of clonidine and yohimbine on locomotion and cutaneous reflexes in the adult chronic spinal cat. Brain Res 1987;437:83-96.
58. Colombo G, Wirz M, Dietz V. Driven gait orthosis for improvement of locomotor training in paraplegic patients. Spinal Cord 2001;39:252-5.
59. Rémy-Néris O, Barbeau H, Daniel O, Boiteau F, Bussel B. Effects of intrathecal clonidine injection on spinal reflexes and human locomotion in incomplete paraplegic subjects. Exp Brain Res 1999;129:433-40.
60. Dietz V, Colombo G, Jensen L, Baumgartner L. Locomotor capacity of spinal cord in paraplegic patients. Ann Neurol 1995;37:574-82.
61. Dietz V, Colombo G, Jensen L. Locomotor activity in spinal man. Lancet 1994;344:1260-3.
62. Gorassini MA, Norton JA, Nevett-Duchcherer J, Roy FD, Yang JF. Changes in locomotor muscle activity after treadmill training in subjects with incomplete spinal cord injury. J Neurophysiol 2009;101:969-79.
63. Ditor DS, Kamath MV, MacDonald MJ, Bugaresti J, McCartney N, Hicks AL *et al*. Effects of body weight-supported treadmill training on heart rate variability and blood pressure variability in individuals with spinal cord injury. J Appl Physiol 2005;98:1519-25.
64. Hidler JM, Wall AE. Alterations in muscle activation patterns during robotic-assisted walking. Clin Biomech 2005;20:184-93.
65. Israel JF, Campbell DD, Kahn JH, Hornby TG. Metabolic costs and muscle activity patterns during robotic- and therapist-assisted treadmill walking in individuals with incomplete spinal cord injury. Phys Ther 2006;86:1466-78.
66. Wu M, Hornby TG, Landry JM, Roth H, Schmit BD. A cable-driven locomotor training system for restoration of gait in human SCI. Gait Posture 2011;33:256-60.
67. Lam T, Pauhl K, Krassioukov A, Eng JJ. Using robot-applied resistance to augment body-weight-supported treadmill training in an individual with incomplete spinal cord injury. Phys Ther 2011;91:143-51.
68. Duschau-Wicke A, Caprez A, Riener R. Patient-cooperative control increases active participation of individuals with SCI during robot-aided gait training. J Neuroeng Rehabil 2010;7:43.
69. Lam T, Wirz M, Lünenburger L, Dietz V. Swing phase resistance enhances flexor muscle activity during treadmill locomotion in incomplete spinal cord injury. Neurorehabil Neural Repair 2008;22:438-46.
70. Hidler J, Neckel N. Inverse-dynamics based assessment of gait using a robotic orthosis. Conf Proc IEEE Eng Med Biol Soc 2006;1:185-8.
71. Dobkin BH, Harkema S, Requejo P, Edgerton VR. Modulation of locomotor-like EMG activity in subjects with complete and incomplete spinal cord injury. J Neurol Rehabil 1995;9:183-90.
72. Behrman AL, Lawless-Dixon AR, Davis SB, Bowden MG, Nair P, Phadke C *et al*. Locomotor training progression and outcomes after incomplete spinal cord injury. Phys Ther 2005;85:1356-71.
73. Lam T, Wirz M, Lünenburger L, Dietz V. Swing phase resistance enhances flexor muscle activity during treadmill locomotion in incomplete spinal cord injury. Neurorehabil Neural Repair 2008;22:438-46.
74. Bolliger M, Banz R, Dietz V, Lünenburger L. Standardized voluntary force measurement in a lower extremity rehabilitation robot. J Neuroeng Rehabil 2008;5:23.
75. Swinnen E, Duerinck S, Baeyens JP, Meeusen R, Kerckhofs E. Effectiveness of robot-assisted gait training in persons with spinal cord injury: a systematic review. J Rehabil Med 2010;42:520-6.
76. Swinnen E, Duerinck S, Baeyens JP, Meeusen R, Kerckhofs E. Effectiveness of robot-assisted gait training in persons with spinal cord injury: a systematic review. J Rehabil Med 2010;42:520-6.
77. Behrman AL, Harkema SJ. Locomotor training after human spinal cord injury: A series of case studies. Physical Therapy 2000;80:688-700.
78. Schmidt H, Sorowka D, Hesse S, Bernhardt R. Development of a robotic walking simulator for gait rehabilitation. Biomed Tech (Berl) 2003;48:281-6.
79. Hesse S, Merholz J, Werner C. Robot-assisted upper and lower limb rehabilitation after stroke: walking and arm/hand function. Dtsch Arztebl Int 2008;105:330-6.
80. Westlake KP, Patten C. Pilot study of Lokomat versus manual-assisted treadmill training for locomotor recovery post-stroke. J Neuroeng Rehabil 2009;6:18.
81. Moreno JC, Del Ama AJ, de Los Reyes-Guzmán A, Gil-Agudo A, Ceres R *et al.* Neurorobotic and hybrid management of lower limb motor disorders: a review. Med Biol Eng Comput 2011;49:1119-30.
82. Hidler J, Nichols D, Pelliccio M, Brady K, Campbell DD, Kahn JH *et al*. Multicenter randomized clinical trial evaluating the effectiveness of the Lokomat in subacute stroke. Neurorehabil Neural Repair 2009;23:5-1.
83. Colombo G, Joerg M, Schreier R, Dietz V. Treadmill training of paraplegic patients using a robotic orthosis. J Rehabil Res Dev 2000;37:693-700.
84. Bovolenta F, Sale P, Dall'Armi V, Clerici P, Franceschini M. Robot-aided therapy for upper limbs in patients with stroke-related lesions. Brief report of a clinical experience. J Neuroeng Rehabil 2011;8:18.
85. Laver KE, George S, Thomas S, Deutsch JE, Crotty M. Virtual reality for stroke rehabilitation. Cochrane Database Syst Rev 2011;9:CD008349.
86. Holden MK. Virtual environments for motor rehabilitation: review. Cyberpsychol Behav 2005;8:187-211.
87. Prange GB, Jannink MJ, Groothuis-Oudshoorn CG, Hermens HJ, Ijzerman MJ. Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke. J Rehabil Res Dev 2006;43:171-84.
88. Buurke JH, Nene AV, Kwakkel G, Erren-Wolters V, Ijzerman MJ, Hermens HJ. Recovery of gait after stroke: what changes? Neurorehabil Neural Repair 2008;22:676-83.
89. Wagenaar RC, Meijer OG, van Wieringen PC, Kuik DJ, Hazenberg GJ, Lindeboom J *et al.* The functional recovery of stroke: a comparison between neuro-developmental treatment and the Brunnstrom method. Scand J Rehabil Med 1990;22:1-8.
90. Buurke JH, Nene AV, Kwakkel G, Erren-Wolters V, Ijzerman MJ, Hermens HJ. Recovery of gait after stroke: what changes? Neurorehabil Neural Repair 2008;22:676-83.
91. Barreca S, Wolf SL, Fasoli S, Bohannon R. Treatment interventions for the paretic upper limb of stroke survivors: a critical review. Neurorehabil NeuralRepair 2003;17:220-6.

92. Mayr A, Kofler M, Quirbach E, Matzak H, Frohlich K, Saltuari L. Prospective, blinded, randomized crossover study of gait rehabilitation in stroke patients using the Lokomat gait orthosis. Neurorehabil Neural Repair 2007;21:307-14.
93. Schwartz I, Sajin A, Fisher I, Neeb M, Shochina M, Katz-Leurer M. The effectiveness of locomotor therapy using robotic assisted gait training in subacute stroke patients: a randomized controlled trial. PM&R 2009;1:516-23.
94. Mehrholz J, Werner C, Kugler J, Pohl M. Electromechanical-assisted training for walking after stroke. Cochrane Database of Systematic Reviews 2007, Issue 4. Art. No.: CD006185.
95. Fisher S, Lucas L, Thrasher TA. Robot-assisted gait training for patients with hemiparesis due to stroke. Top Stroke Rehabil 2011;18:269-76.
96. Geroin C, Picelli A, Munari D, Waldner A, Tomelleri C, Smania N. Combined transcranial direct current stimulation and robot-assisted gait training in patients with chronic stroke: a preliminary comparison. Clin Rehabil 2011;25:537-48.
97. Wagner TH, Lo AC, Peduzzi P, Bravata DM, Huang GD, Krebs HI *et al.* An economic analysis of robot-assisted therapy for long-term upper-limb impairment after stroke. Stroke 2011;42:2630-2.