Published in final edited form as:

Phys Med Rehabil Clin N Am. 2013 May ; 24(2): 305–323. doi:10.1016/j.pmr.2012.11.005.

Technological Advances in Interventions to Enhance Post-Stroke Gait

Lynne R. Sheffler, M.D.^{1,3,4} and John Chae, M.D.^{1,2,3,4}

¹Department of Physical Medicine and Rehabilitation, Case Western Reserve University, Cleveland, OH

²Department of Biomedical Engineering, Case Western Reserve University, Cleveland, OH

³Department of Physical Medicine and Rehabilitation, MetroHealth Medical Center, Cleveland, OH

⁴Cleveland Functional Electrical Stimulation Center, Cleveland, OH

Synopsis

This article provides a comprehensive review of specific rehabilitation interventions used to enhance hemiparetic gait following stroke. Neurologic rehabilitation interventions may be either therapeutic resulting in enhanced motor recovery or compensatory whereby assistance or substitution for neurological deficits results in improved functional performance. Included in this review are lower extremity functional electrical stimulation (FES), body-weight supported treadmill training (BWSTT), and lower extremity robotic-assisted gait training. These post-stroke gait training therapies are predicated on activity-dependent neuroplasticity which is the concept that cortical reorganization following central nervous system injury may be induced by repetitive, skilled, and cognitively engaging active movement. All three interventions have been trialed extensively in both research and clinical settings to demonstrate a positive effect on various gait parameters and measures of walking performance. However, more evidence is necessary to determine if specific technology-enhanced gait training methods are superior to conventional gait training methods. This review provides an overview of evidence-based research which supports the efficacy of these three interventions to improve gait, as well as provide perspective on future developments to enhance post-stroke gait in neurologic rehabilitation.

Keywords

gait; hemiparesis; motor relearning; neuroplasticity

Introduction

This article provides a comprehensive review of specific rehabilitation interventions used to enhance hemiparetic gait following stroke. Broadly speaking, neurologic rehabilitation

© 2012 Elsevier Inc. All rights reserved.

Address all correspondence to: Lynne R. Sheffler, M.D., Assistant Professor, Department of Physical Medicine and Rehabilitation, MetroHealth Medical Center, 2500 MetroHealth Drive, Cleveland, OH 44109, lsheffler@metrohealth.org, Ph 216.778.3472, FAX 216.778.5560.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

interventions may be considered either therapeutic or compensatory. Post-stroke therapeutic interventions may improve gait performance by various motor relearning mechanisms including improved motor strength or enhanced motor control. Motor relearning is defined as “the recovery of previously learned motor skills that have been lost following localized damage to the central nervous system.”¹ Compensatory interventions may improve gait performance by providing assistance or by substituting for neurological deficits to improve function. The specific spatiotemporal, kinematic, and kinetic parameters of gait that distinguish hemiparetic gait from other upper motor neuron gait patterns are described elsewhere in this text. Included in this review are specific clinical and research applications of rehabilitation interventions which may enhance post-stroke gait including lower extremity functional electrical stimulation (FES), body-weight supported treadmill training (BWSTT), and lower extremity robotic-assisted gait training. These three post-stroke gait training therapies are all predicated on activity-dependent neuroplasticity which is the concept that cortical reorganization following central nervous system injury may be induced by repetitive, skilled, and cognitively engaging active movement. This review will not cover spasticity management, lower extremity orthotics or specific physical therapy therapeutic treatments such as neurodevelopmental technique (NDT). Instead, this review attempts to provide a concise overview of evidence-based research which supports the efficacy of the three interventions mentioned above, as well as provide perspective on future developments to enhance post-stroke gait in neurologic rehabilitation.

Functional Electrical Stimulation

Neuromuscular electrical stimulation (NMES) refers to the activation of paretic or paralyzed muscles via stimulation of an intact lower motor neuron (LMN). The term functional electrical stimulation was originally coined by Moe and Post² to describe the use of NMES to activate paretic muscles in a magnitude and sequence so as to directly facilitate a functional task such as walking. A lower extremity neuroprosthesis is an FES device or system designed to enhance functional walking and the term “neuroprosthetic effect” describes the enhancement of walking performance that results when the neuroprosthesis is utilized. This effect may be evident by improved gait efficiency (for example, energy expenditure) or by improved spatiotemporal, kinematic, or kinetic parameters of gait (for example, walking velocity, paretic ankle dorsiflexion angle at heelstrike, or paretic plantarflexion power at push-off). Evolving basic science and clinical studies on central motor neuroplasticity support the role of active repetitive movement training of a paretic limb to enhance motor relearning and thus lower extremity FES applications have also been proposed for therapeutic purposes in hemiparesis. The rationale for a therapeutic role of FES is that if active repetitive movement training facilitates motor recovery, then theoretically, FES-mediated repetitive movement training may also facilitate post-stroke motor recovery. A recent review of the clinical and research applications of NMES in neurorehabilitation includes an overview of FES neurophysiology, FES componentry, and therapeutic applications of research and commercially available FES devices.³

Neurophysiology of FES

Most clinical FES applications are limited to patients with upper motor neuron dysfunction, because FES is dependent on the LMN being intact. Either the motor point of the nerve proximal to the neuromuscular junction or the peripheral nerve itself can be directly stimulated by clinical and research-based FES systems. The threshold for eliciting a nerve fiber action potential is 100 to 1000 times less than the threshold for muscle fiber stimulation.⁴ An action potential (AP) induced by an FES system is identical to the “all or none” phenomenon of the AP produced by natural physiologic means. However, an AP produced by normal physiologic mechanisms initially recruits the smallest diameter neurons

prior to recruitment of larger diameter fibers, such as alpha motor neurons.⁵ The nerve fiber recruitment pattern induced by FES differs from a physiologic AP by following the principle of “reverse recruitment order”. Reverse recruitment order means that the nerve stimulus threshold is inversely proportional to the diameter of the neuron. Thus, large diameter nerve fibers, which innervate larger motor units, are recruited preferentially. Adjustment of stimulus parameters such as stimulus amplitude, pulse width, and frequency^{4, 6-7} thus affect both nerve fiber recruitment and resultant muscle contraction force characteristics. The minimum stimulus frequency that can generate a fused muscle response is approximately 12.5 Hz. While stimulation frequencies higher than 12.5 Hz can generate higher muscle forces, there is a risk of muscle fiber fatigue and resultant decrease in muscle contractile force. An efficient FES system is designed to use the minimal stimulus frequency that produces a fused response⁸⁻¹⁰ with ideal stimulation frequencies ranging from 18-25 Hz for lower-limb applications.

Components of FES systems

Most research and commercially available FES systems for neurorehabilitation fall into two broad categories based on electrode type: transcutaneous (surface) electrode and implanted electrode systems. A transcutaneous electrode is applied directly to the skin and stimulates either the peripheral nerve or the motor point of the underlying muscle. A transcutaneous electrode is the simplest electrode available and uses an external lead to connect directly to the neurostimulator device. An electrical current is created when two electrodes are placed in either a monopolar or bipolar configuration in relation to each other. The risk of tissue injury in patients with cognitive and/or sensory deficits may be increased with a transcutaneous electrode system and thus specific neurologic deficits must be evaluated prior to usage. Other common limitations associated with transcutaneous electrode systems in the stroke patient population include intolerance due to activation of cutaneous pain receptors, poor muscle selectivity, inconsistency with electrode positioning, insecure fixation on a moving limb, skin irritation associated with the electrode, and cosmetic concerns³.

The percutaneous intramuscular electrode¹¹ is one type of implantable electrode. The placement of a percutaneous electrode is a minimally invasive procedure, however, lead wires which exit the skin are required to connect the electrode to the neurostimulator. The advantages and disadvantages of the percutaneous electrode has been well described previously.³ The advantages of the percutaneous electrode are the elimination of skin resistance and cutaneous pain issues, greater muscle selectivity, and lower stimulation currents. Safety risks include lead displacement or breakage, infection, and granuloma formation associated with retained electrode fragments. The cumulative long-term failure rate of percutaneous electrodes varies between 56% and 80%,¹²⁻¹⁴ which generally limits their use to less than 3 months. As a result, the most common application of percutaneous electrodes is for time-limited therapeutic purposes or research applications.

Epimysial,¹⁵⁻¹⁸ epineural, intraneural,¹⁹⁻²¹ and cuff²²⁻²⁵ electrodes are all types of surgically implanted electrodes which may be used for longer-term neurostimulation applications. These electrodes are surgically placed above the muscle, above the nerve, within the nerve, or around the nerve, respectively. These types of implanted electrodes all connect to implanted lead wires and require the implantation of the neurostimulator. A radio-frequency (RF) telemetry link relays both power and command instructions to the neurostimulator from an external control unit. An implanted peroneal nerve stimulation (PNS) device²⁶⁻²⁸ is an example of a clinically viable neuroprosthesis which utilizes implantable electrodes.

Correlating user intent to functional performance, particularly in the application of a lower extremity neuroprosthesis, presents significant challenges in the design of FES control systems. Many upper extremity clinical FES systems employ open-loop control (preset pattern of stimulation) with sensory feedback limited to residual visual and proprioceptive input. A closed-loop control system for continuous real-time modification of the stimulation pattern based on sensory feedback offers maximal advantage for a lower extremity neuroprosthesis. A transcutaneous PNS device is an example of a neuroprosthesis that utilizes a closed-loop control system such as a simple heel switch²⁹, tilt sensor³⁰, or acceleration sensor³¹.

Lower Extremity FES in Hemiparesis

The initial application of a neuroprosthesis in hemiparesis was the transcutaneous PNS device for correction of ankle dorsiflexion weakness associated with upper motor neuron dysfunction. In a 1961 publication, Lieberman³² first described a stimulator that dorsiflexed the ankle during the swing phase of gait. Burridge et al²⁹ later reported that chronic stroke survivors treated with PNS and physical therapy (PT) had a significant increase in walking velocity and decrease in energy expenditure measured by the physiologic cost index as compared to a control group who received PT only. The application of surface PNS has more recently been proposed as an alternative to an ankle-foot orthosis (AFO) based on other favorable neuroprosthetic effects of PNS.³³⁻³⁵ Studies of hemiparetic subjects treated with neuroprosthetic applications of PNS have also reported possible therapeutic effects including enhanced walking speed,^{34, 36-38} increased maximal isometric contraction of the ankle dorsiflexors and plantarflexors,³⁹ increased dorsiflexion torque,⁴⁰ increased agonist EMG activity and decreased EMG co-contraction ratios,⁴¹ increased maximum root mean square (measure of muscle output capacity),³⁸ decreased calf spasticity,³⁸ and improved ankle control,⁴² outcomes which were all measured while the subject was not wearing the device. Studies which have specifically compared the neuroprosthetic effect of a PNS to the orthotic effect of an AFO in hemiplegic gait^{29, 36-37, 43-44} have also facilitated broader clinical prescription and usage of these devices.

The Food and Drug Administration (FDA) has approved three surface PNS devices for clinical use in the United States. These devices are the Odstock Dropped Foot Stimulator® (ODFS) (Odstock Medical Limited, Salisbury, UK) (Figure 1), Ness L300® Footdrop System (Bioness Inc., Valencia, CA) (Figure 2), and the WalkAide® System (Innovative Neurotronics, Austin, TX)(Figure 3). The ODFS also carries the CE Mark Approval by the European Union. The ODFS and the Ness L300® device utilize heel switches and the WalkAide device utilizes a tilt sensor as a control system to time stimulation to the swing phase of gait. The clinical use of these devices may be limited in stroke patients with skin breakdown or edema, lower extremity sensory deficits, cognitive deficits, ankle range-of-motion limitations, plantarflexion spasticity, cerebellar ataxia, and/or muscle fatigue. Common reasons for lack of efficacy of a surface PNS device include patient intolerance to surface stimulation, difficulty with electrode placement, insufficient medial-lateral control during stance phase, persistent genu recurvatum, and/or lack of rehabilitation support staff to assist with device programming.

The technical limitations of transcutaneous devices may ultimately be solved with the further refinement of implantable neurostimulation systems. Early studies first reported improvements in spatiotemporal gait parameters following implantation of a single channel PNS device.⁴⁵⁻⁴⁶ While an implantable PNS device is not presently FDA-approved in the United States, multi-channel implantable PNS devices have recently undergone clinical investigation in Europe. A dual channel device developed at the University of Twente and Roessingh Research and Development (The Netherlands) stimulates the deep and superficial

peroneal nerves for better control and balance of ankle dorsiflexion, eversion, and inversion.⁴⁷ A four-channel device, developed at Aalborg University (Denmark) utilizes a nerve cuff electrode with 4 tri-polar electrodes, oriented to activate different nerve fibers within the common peroneal nerve.⁴⁸ Both devices have received the CE Mark Approval in the European Union and clinical experience with these devices is now being reported. Recent clinical trials which have evaluated the efficacy of an implantable PNS device report a neuroprosthetic effect on walking speed²⁷, paretic double support and non-paretic single support²⁸, and ankle dorsiflexion angle during swing.²⁸ No PNS therapeutic effect was found in a study which compared 6 months of ambulation using an implantable, 2-channel peroneal nerve stimulator to an AFO²⁶; however, increased voluntary muscle output of the TA and GS muscles in the PNS group were hypothesized to be evidence of neuroplasticity.

Several multichannel transcutaneous stimulation systems have been trialed which incorporate knee and hip flexion and extension as well as ankle dorsiflexion⁴⁹⁻⁵¹. The rationale for these more complex stimulation systems is that post-stroke gait deviation associated with hemiplegia is not limited to ankle dysfunction nor remedied by correction of footdrop alone. However, lower-limb transcutaneous systems are particularly limited by reduced muscle selectivity, poor consistency of stimulation, and discomfort associated with sensory stimulation of larger, weight-bearing lower extremity muscles. From a clinical standpoint, as the number of electrodes increases, transcutaneous systems are increasingly difficult to clinically implement³. However, commercially available PNS devices including the Ness L300® Plus System and the Odstock 2 Channel Stimulator device have recent modifications which allow for activation of additional muscles groups such as the quadriceps and/or hamstring muscles. Multichannel percutaneous lower-limb systems⁵²⁻⁵³ remain limited to research applications or time-limited therapeutic interventions intended to facilitate motor relearning as opposed to longer-term providing a neuroprosthetic solution.

Summary

In summary, a transcutaneous PNS device may be an appropriate clinical alternative to an AFO in select hemiparetic stroke patients. Neurologic and medical issues which affect patient safety need to be considered and a device trial under the guidance of a trained physical therapist or other rehabilitation professional is recommended prior to device prescription. Additional practical issues including access to longer-term technical support and comparative device (PNS versus AFO) costs should also be considered. Additional research is necessary to determine the clinical efficacy of a two channel transcutaneous PNS device which incorporates quadriceps and/or hamstring stimulation. Clinical experience outside of the United States suggests an implantable PNS device may be a viable neuroprosthesis for select patients. However, potential benefits must be tempered with the risks and costs associated with an invasive procedure. At present, multichannel percutaneous lower-limb FES systems remain limited to research and/or time-limited therapeutic applications. Lastly, research is increasingly focusing on new technologies such as harnessing cortical control signals that may provide an enhanced means of interfacing with a neuroprosthesis⁵⁴⁻⁵⁵ and developing multichannel networked implantable neuroprostheses systems⁵⁶ which may someday address both upper and lower limb paralysis associated with central nervous system injury.

Body-Weight Supported Treadmill Training in Hemiparesis

Body weight supported treadmill training (BWSTT) is an adaptive therapeutic training modality which allows otherwise nonambulatory or limited ambulatory hemiparetic stroke patients to participate in task-specific gait training. The patient is fitted with a harness which provides partial support of his/her full body weight as he/she is suspended over the treadmill

surface. With the assistance of one or several physical therapists to facilitate paretic lower limb placement, balance, and limb sequencing, the patient is able to participate in repetitive gait training exercises while upright and partially weight-bearing. The primary advantage of any BWSTT method is that the subject is able to safely be upright with limited physical assistance which allows the treating physical therapist to observe and correct the gait pattern to improve functional performance.⁵⁷ Overground walking with partial body weight support (BWS), without the use of a treadmill, has been shown to improve walking in hemiparetic stroke patients.⁵⁸⁻⁵⁹ In a recent study, self-selected walking speeds over a 15-meter walkway increased 17% on average when hemiparetic subjects walked with some level of BWS as compared to the no BWS condition.⁵⁹ Similarly, oxygen consumption (as measured by VO₂) and heart rate were improved at both self-selected and maximum walking speeds during walking with 30% BWS on a treadmill as compared to unsupported treadmill walking.⁶⁰ Hesse et al⁶¹ evaluated the gait patterns of hemiparetic subjects walking on a treadmill with 0%, 15% and 30% BWS as compared to overground walking. BWSTT was associated with a more prolonged single stance period of the paretic limb, greater gait symmetry, less plantar flexor spasticity, and a more regular activation pattern of the gastrocnemius/soleus and anterior tibialis muscles as compared with floor walking. As compared to overground walking or overground training using partial BWS, BWSTT may allow the therapist to achieve a more symmetric, efficient hemiparetic gait pattern within a more practical physical space.

Clinical Application of BWSTT Gait Training

Commercially available body weight supported devices may have both over-ground and treadmill capability for use in a therapy gym or home setting. Examples of such devices include the body weight support mechanism of the Lokomat @System (Levi BWS, Hocoma, Zurich, Switzerland), the LiteGait® device (LiteGait, Tempe, AZ) and the Gait Trainer 3™ Biodex Gait Training System (Biodex Medical Systems, Inc., Shirley, NY). The prescription of specific parameters including percent body weight support, speed of the treadmill, support stiffness, and handrail hold can affect treatment outcomes in hemiparetic patients⁶²⁻⁶³. Thus, there may be significant variability in the application of the BWS gait training system and training protocols between clinical settings. In a study of the effect of treadmill speed used during BWS gait training, the greatest improvement in self-selected walking velocity occurred with fast training speeds⁶⁴ thus training at speeds comparable with normal walking velocity may be more effective than training at lower speeds. Specific objective clinical targets, for example, heart rate and perceived exertion, can be achieved and/or monitored during BWSTT locomotor training. Patient ease of usage has also been reported as reflected in a recent study⁶⁵ which demonstrated that stable walking using BWSTT, as measured by spatiotemporal gait parameters including cadence, step length, and trunk symmetry, was achieved within a 5-min walking trial.

BWSTT Gait Training and Post-Stroke Neuroplasticity

Recent research has focused on determining if BWSTT has an effect on post-stroke neuroplasticity. A therapeutic benefit by neuroplastic mechanisms is largely predicated on research in spinal cord injury which has demonstrated the malleability of the CNS post-injury in response to locomotor training⁶⁶⁻⁷¹. Central pattern generators (CPG), neuronal circuitry located within the spinal cord, produce the coordinated activation of flexor and extensor motoneurons during locomotion⁷²⁻⁷³ and segmental reflex pathways control the basic operation of the CPG circuitry responsible for locomotion.⁷⁴ Supraspinal input⁷⁵ to the spinal circuitry, however, is clearly essential for both human and animal walking. Locomotor training has been shown to change the excitability of simple reflex pathways as well as more complex circuitry, and adaptation occurs at both spinal and supraspinal levels

in animals following spinal lesions.⁷⁶ Beneficial therapeutic effects of early sustained locomotor training after both central or peripheral lesions, based on evidence of plasticity of spinal and supraspinal locomotor control mechanisms, has thus been advocated.⁷⁷

Researchers have used various neuroimaging modalities to test the hypothesis that BWSTT may influence post-stroke central neuroplasticity. Enzinger et al⁷⁸ applied an ankle dorsiflexion functional MRI paradigm to relate brain activity changes in chronic stroke subjects to performance gains after 4 weeks of BWSTT gait training. At the end of treatment, walking endurance, as reflected by the 2-minute walking distance, improved and clinical performance correlated to an increase in brain activity in the bilateral primary sensorimotor cortices, the cingulate motor areas, and the caudate nuclei bilaterally, and in the thalamus of the affected hemisphere. The authors concluded that despite subcortical contributions to gait control, walking improvements secondary to BWSTT gait training were associated with cortical activation changes. Another study used an optical imaging system to evaluate the effect of BWSTT on cortical activation during gait in hemiparetic subjects as compared to controls.⁷⁹ Treatment with BWSTT in the hemiparetic subjects was associated with changes in activation in the sensorimotor cortex (SMC) which correlated with cadence ($P<0.05$). Improvement of asymmetry in SMC activation also correlated with improvement of asymmetric gait ($P<0.05$). The authors concluded that BWSTT might improve the efficacy of SMC function in patients with stroke. Further research is necessary to determine if post-stroke BWSTT therapy has central effects and if those effects translate into clinically significant change in motor impairment and/or functional mobility outcome measures.

Clinical Efficacy of Post-Stroke BWSTT Gait Training

Multiple studies have suggested beneficial effects of BWSTT gait training in hemiparetic patients on outcomes including walking speed⁸⁰⁻⁸³, balance⁸¹⁻⁸², walking capacity⁸²⁻⁸⁴, motor recovery⁸¹⁻⁸², and patient perception of walking ability⁸⁴. Visitin et al⁸¹ compared the effects of BWSTT gait training (40% weight support) and treadmill gait training without BWS. After 6 weeks of training, the BWSTT group scored significantly higher on functional balance, motor recovery, overground walking speed, and overground walking endurance outcome measures. At 3 months post-treatment, the BWSTT group continued to score significantly higher than the control group on walking speed and motor recovery measures. In a study that stratified subjects according to initial overground walking speed, endurance, balance, and motor recovery, Barbeau et al⁸² found that 6 weeks of BWSTT training resulted in greater walking speed, endurance, functional balance and motor recovery change than did gait training without BWS. BWSTT was more beneficial to subjects who were older or had a greater baseline level of gait impairment. A recent study⁸⁵ explored which kinematic and kinetic gait parameters were most associated with improved walking speed in hemiparetic subjects who were responsive to a 6-week BWSTT program. Subjects who improved their self selected walking speeds by greater than 0.08 m/s demonstrated greater increases in terminal stance hip extension, hip flexion power, and intensity of soleus muscle EMG activity during walking.

While beneficial effects have been reported, a Cochrane review⁸⁶ and several recent randomized controlled trials⁸⁷⁻⁹⁰ show that the superiority of BWSTT gait training over standard of care gait training interventions has not been established. In a study which compared BWSTT to conventional overground gait training in nonambulatory subacute (< 6 wks post-stroke) stroke subjects, Franceschini et al⁸⁷ reported that walking speed and capacity, functional ambulation performance, and balance were significantly improved in both groups at the end of 4 weeks of treatment and at the 6-month follow-up. Similarly, Nilsson et al⁸⁹ found no statistically significant difference in Functional Independence Measure score, walking speed, Fugl-Meyer score, and the Berg Balance score gains at end-

of-treatment and at the 10-month follow-up in acute/subacute post-stroke subjects randomized to receive either BWSTT or overground walking training. More recently, Duncan et al⁹⁰ reported on the Locomotor Experience Applied Post-stroke (“LEAPS”) trial, which is the largest study to date to evaluate the efficacy of BWSTT for post-stroke gait training. The LEAPS trial enrolled 408 subacute hemiparetic stroke subjects (<2 mos post-CVA) and stratified the subjects by level of walking impairment. The subjects were then randomized into one of 3 gait training groups: 1) BWSTT starting at 2 months post-stroke (“early locomotor training”); 2) BWSTT starting at 6 months post-stroke (“late locomotor training”); and 3) home exercise program (“home exercise”) starting at 2 months post-stroke. The primary outcome measure was the proportion of subjects who had improved functional walking ability at 1 year post-stroke. At one year, all three groups had similar improvements in walking speed, motor recovery, balance, functional status, and quality of life. The authors concluded that gait training which included the use of BWSTT was not superior to progressive exercise at home managed by a physical therapist. Based on current evidence, Dobkin and Duncan⁹¹ recently concluded that BWSTT does not lead to better outcomes than a comparable dose of progressive over-ground training post-stroke and should not be routinely provided to stroke survivors in place of conventional therapy.

Summary

In summary, BWSTT is a gait training modality which allows otherwise nonambulatory or limited ambulatory hemiparetic stroke patients to participate in task-specific gait training. BWSTT gait training allows a hemiparetic patient to safely weight-bear with limited physical assistance while the treating physical therapist focuses on optimizing the gait pattern. BWSTT systems are available for clinical use and are routinely incorporated into post-stroke clinical gait training programs. Research supports a beneficial effect of BWSTT on hemiparetic walking speed and capacity, functional balance, and post-stroke functional ambulation. Current research is focused on both identifying a neuroplastic mechanism which may explain a therapeutic effect of BWSTT gait training and combining BWS methods with other rehabilitation modalities, such as FES⁹², to maximize post-stroke gait rehabilitation outcomes. Recent randomized controlled clinical trials have not, however, established the superiority of BWSTT over other conventional post-stroke gait training interventions.

Robotic-Assisted Gait Training for Hemiparesis

Clinical outpatient stroke rehabilitation programs are increasingly incorporating robotic devices for post-stroke gait training. Robotic-assisted gait training involves the use of a powered robot exoskeleton to facilitate repetitive, prolonged, and uniform lower extremity joint and limb movement. Most robotic devices for gait training incorporate some form of body weight support. While the Lokomat ®System (Hocoma, Zurich, Switzerland), which combines a robotic orthosis with a body weight support treadmill system, was introduced as a gait training intervention in spinal cord injury in 2003⁹³, post-stroke gait training using robotic devices was first described as early as the 1990's. Proposed advantages of robotic training include enhanced safety for more severely disabled patients, ability to begin gait training earlier in the post-stroke recovery period, increased training time per session, and a decreased physical burden to the treating therapist⁹⁴. Research also suggests there may be exercise benefits, including improved body tissue composition⁹⁵ and improved metabolic and cardiac responses⁹⁶ following lower-limb robotic gait training. Robots provide the ability to individualize a post-stroke gait training program to the specific biomechanical needs of a patient⁹⁷ and thus may be efficacious for stroke survivors across a broad spectrum of motor impairment levels.⁹⁸ Robotics may be uniquely suited as an early post-stroke intervention due to the ability to match task difficulty to patient abilities as motor recovery occurs⁹⁹. In a recent review, Hussain et al¹⁰⁰ described rehabilitation engineering

design considerations for treadmill based robotic gait training devices including type of neurologic injury, level of disability, actuation methods, and training strategies.

Efficacy of Robotic-Assisted Gait Training

Pilot studies have demonstrated improvement in gait velocity¹⁰¹⁻¹⁰³, 6-minute walking distance^{102, 104}, balance¹⁰¹, motor impairment¹⁰⁴, spasticity¹⁰⁴, electromyographic muscle symmetry¹⁰⁵, and functional ambulation performance¹⁰¹ associated with a robotic gait training system. Mayr et al¹⁰⁴ reported on a randomized crossover study which enrolled sixteen subacute (< 3 mos) subjects who received robotic gait training alternating with conventional physical therapy for a total of 9 weeks of treatment. Performance on the EU-Walking Scale, Rivermead Motor Assessment Scale, 6-minute walking distance, Medical Research Council Scale (motor strength), and Ashworth Scale (spasticity) was significantly more improved during the robotic training phase than during the conventional treatment phase within each 3-week interval. In a more recent observational study, Conesa et al¹⁰¹ reported that eighty percent of 103 subacute inpatient stroke subjects who received 4 weeks of robotic gait training followed by 4 weeks of manual gait training improved walking speed by more than 0.2 m/s and increased at least one point on the Functional Ambulation Category. A recent review of robotic-assisted gait training in neurological injury also supports that locomotor training with robotic assistance is beneficial for improving walking function in individuals following a stroke.¹⁰⁶

Robotic-Assisted Gait Training as Compared to Conventional Therapy

Several randomized clinical trials¹⁰⁷⁻¹¹¹ have suggested that robotic training is better than conventional gait training. In a study of 67 subacute (< 3 months) stroke patients randomized to 6 weeks of robotic-assisted gait training or conventional physical therapy¹¹⁰, the robotic group demonstrated greater gains in both the National Institute of Health Stroke Scale score and the ability to walk independently at the end of treatment. Stroke survivors with greater motor impairments may benefit more from robotic therapy. Morone et al¹⁰⁸ stratified 48 subacute stroke subjects into two motor impairment groups and then randomized them to receive either 3 months of robotic-assisted training (20 sessions) plus conventional therapy, or conventional gait training alone. The lower motricity group who received robotic training demonstrated significant improvement in the Functional Ambulation Category, Rivermead mobility index, and the 6-minute walking distance whereas in the higher motricity groups, robotic and conventional therapies were equivalent. In a follow-up analysis¹⁰⁹, the greater efficacy of the robotic-assisted program observed in patients with greater motor impairment was found to be sustained after 2 years. A recent Cochrane review which evaluated 8 trials (414 subjects) concluded that stroke survivors who received robotic-assisted gait training in combination with physical therapy were more likely to achieve independent walking than patients receiving gait training without robotic devices¹¹².

In contrast, there are several studies which suggest that post-stroke robotic gait training is either no more effective^{95, 113-114} or less effective than conventional gait training¹¹⁵⁻¹¹⁷. In an early study of 4 weeks of robotic gait training in acute stroke survivors⁹⁵, both the robotic and control groups improved, but there was no significant difference in gait speed or independence between the groups. Fisher¹¹³ randomized twenty stroke survivors to receive either robotic-assisted gait training on a treadmill plus conventional PT versus conventional PT alone. Similarly, at the end of 24 treatment sessions, both groups showed significant improvement on an 8-meter walk test, 3-minute walk test, and the Tinetti balance assessment; however, there was no difference between groups. Hornby¹¹⁶ evaluated the effect of robotic versus therapist-assisted locomotor training in 48 chronic stroke survivors

stratified by level of locomotor deficit. At end of treatment, greater improvement in walking speed and paretic single stance time was observed in the therapist-assist group. Similarly, of 63 subacute (< 6 mos) stroke survivors randomized to receive either 24 sessions of robotic or conventional gait training¹¹⁵, those who received conventional training experienced significantly greater gains in walking speed and 6-minute walking distance than those who received robotic training. These differences were noted at end of treatment and were maintained at 3 months post-treatment. The authors concluded that the diversity of conventional gait training interventions appeared to be more effective than robotic-assisted gait training for improving walking ability. Dobkin and Duncan⁹¹ recently concluded that current evidence does not support that robotic-assisted step training leads to better post-stroke mobility outcomes than a comparable dose of over-ground gait training and recommend that robotic gait therapy should not be routinely provided in place of conventional therapy.

Robotic-Assisted Therapy Plus Virtual Reality for Gait Training

The efficacy of combining lower extremity robotics with virtual reality to improve gait has been evaluated¹¹⁸⁻¹²². Forrester¹¹⁸ reported on eight chronic stroke survivors who were trained in dorsiflexion and plantarflexion movement by playing video games with a robotic ankle device. At the end of the 6-week training period, improvements were noted in paretic ankle control, walking speed, and single and double support times. Mirelman¹²⁰ randomized 18 stroke survivors to receive robotic gait training or robotic gait training combined with virtual reality stimulation. At the end of four weeks of training, the virtual reality group demonstrated a significantly larger increase in ankle power generation at push-off¹²⁰, change in ankle ROM¹²⁰, walking speed¹²¹, distance walked¹²¹, and community ambulation¹²¹. The differences noted in spatiotemporal performance were maintained at 3 months post-treatment¹²¹. The authors concluded that lower extremity robotic training coupled with virtual reality improved walking ability in stroke survivors and was superior to robotic training alone. Further dose-matched randomized clinical trials which enroll a larger number of subjects are indicated to compare the efficacy of post-stroke robotic-assisted gait training with virtual reality to conventional gait therapy.

Summary

In summary, robotic-assisted gait training is a modality that provides repetitive, prolonged, and uniform lower extremity joint and limb movement. Robotic gait training generally incorporates some form of body weight support. Robotic-assisted gait training systems are being investigated in research applications and are increasingly being incorporated into post-stroke clinical gait training programs. Research supports a beneficial effect of robots on hemiparetic walking speed, walking distance, and functional performance. Randomized controlled clinical trials have not, however, established the superiority of robotic-assisted gait training over other conventional post-stroke gait training interventions. Lastly, current rehabilitation engineering research is focused on robotic design considerations including improving the patient-machine robotic interface and combining robotics with other modalities, including virtual reality, to maximize post-stroke mobility outcomes.

Conclusions

Maximizing lower extremity motor recovery and functional mobility following stroke is a primary goal for all hemiparetic stroke survivors participating in stroke rehabilitation programs. Provided in this review is a comprehensive overview of the evidence-based research which both supports and disputes the efficacy of lower extremity FES, BWS-TT, and robotic-assisted gait training for the treatment of hemiparetic gait. All three

interventions, which have been trialed extensively in both research and clinical settings, demonstrate a positive effect on various gait parameters and measures of walking performance, however, more evidence is necessary to determine if specific technology-enhanced gait training methods are superior to conventional gait training methods. Additionally, further research is necessary to determine how available gait training technologies can be tailored to the specific gait characteristics of the patient. Lastly, future studies should focus on evidence of a peripheral and/or central mechanism underlying the therapeutic or compensatory effect of these interventions to further facilitate translation of these technology-based therapies into the clinical care of patients.

Acknowledgments

This work was supported in part by grant K23HD060689 from the National Institute for Child Health and Human Development.

References

1. Lee RG, van Donkelaar P. Mechanisms underlying functional recovery following stroke. *Can J Neurol Sci.* 1995; 22:257–63. [PubMed: 8599767]
2. Moe JH, Post HW. Functional electrical stimulation for ambulation in hemiplegia. *J Lancet.* 1962; 82:285–8. [PubMed: 14474974]
3. Sheffler LR, Chae J. Neuromuscular electrical stimulation in neurorehabilitation. *Muscle Nerve.* 2007; 35:562–90. [PubMed: 17299744]
4. Mortimer, JT. Motor prostheses. In: Brookhart, JM.; Mountcastle, VB., editors. *Handbook of Physiology-The Nervous System II.* American Physiological Society; Bethesda, MD: 1981. p. 155-87.
5. Henneman E. Relation between size of neurons and their susceptibility to discharge. *Science.* 1957; 126:1345–7. [PubMed: 13495469]
6. Szlavik RB, de Bruin H. The effect of stimulus current pulse width on nerve fiber size recruitment patterns. *Med Eng Phys.* 1999; 21:507–15. [PubMed: 10624746]
7. Adrian, E. *The Physical Background of Perception.* Clarendon Press; Oxford: 1946.
8. Kugelberg E, Edstrom L. Differential histochemical effects of muscle contractions on phosphorylase and glycogen in various types of fibres: relation to fatigue. *J Neurol Neurosurg Psychiatry.* 1968; 31:415–23. [PubMed: 5709825]
9. McNeal DR. Analysis of a model for excitation of myelinated nerve. *IEEE Trans Biomed Eng.* 1976; 23:329–37. [PubMed: 1278925]
10. Bigland-Ritchie B, Jones DA, Woods JJ. Excitation frequency and muscle fatigue: electrical responses during human voluntary and stimulated contractions. *Exp Neurol.* 1979; 64:414–27. [PubMed: 428516]
11. Memberg WPP, Keith MH. A surgically implanted intramuscular electrode for an implantable neuromuscular stimulation system. *IEEE Trans Biomed Eng.* 1994; 2:80–91.
12. Smith BT, Betz RR, Mulcahey MJ, Triolo RJ. Reliability of percutaneous intramuscular electrodes for upper extremity functional neuromuscular stimulation in adolescents with C5 tetraplegia. *Arch Phys Med Rehabil.* 1994; 75:939–45. [PubMed: 8085926]
13. Knutson JS, Naples GG, Peckham PH, Keith WM. Electrode fracture rate and occurrences of infection and granuloma associated with percutaneous intramuscular electrodes in upper-limb functional electrical stimulation application. *J Rehabil Res Dev.* 2003; 39:671–84. [PubMed: 17943669]
14. Memberg WD, Peckham PH, Thorpe GB, Keith MW, Kicher TP. An analysis of the reliability of percutaneous intramuscular electrodes in upper extremity FNS applications. *IEEE Trans Rehabil Eng.* 1993; 1:126–32.
15. Grandjean PA, Mortimer JT. Recruitment properties of monopolar and bipolar epimysial electrodes. *Ann Biomed Eng.* 1986; 14:53–66. [PubMed: 3706855]

16. Waters RL, Campbell JM, Nakai R. Therapeutic electrical stimulation of the lower limb by epimysial electrodes. *Clin Orthop Relat Res.* 1988;44–52. [PubMed: 3261219]
17. Kilgore KL, Peckham PH, Keith MW, et al. Durability of implanted electrodes and leads in an upper-limb neuroprosthesis. *J Rehabil Res Dev.* 2003; 40:457–68. [PubMed: 15077658]
18. Uhlar JP, Triolo RJ, Kobetic R. The use of selective electrical stimulation of the quadriceps to improve standing function in paraplegia. *IEEE Trans Rehabil Eng.* 2000; 8:514–22. [PubMed: 11204043]
19. Bowman BR, Erickson RC 2nd. Acute and chronic implantation of coiled wire intraneural electrodes during cyclical electrical stimulation. *Ann Biomed Eng.* 1985; 13:75–93. [PubMed: 3873885]
20. Hoffer JA, Loeb GE. Implantable electrical and mechanical interfaces with nerve and muscle. *Ann Biomed Eng.* 1980; 8:351–60. [PubMed: 7027837]
21. Nannini N, Horch K. Muscle recruitment with intrafascicular electrodes. *IEEE Trans Biomed Eng.* 1991; 38:769–76. [PubMed: 1937510]
22. Juch PJ, Minkels RF. The strap-electrode: a stimulating and recording electrode for small nerves. *Brain Res Bull.* 1989; 22:917–8. [PubMed: 2765951]
23. Naples GG, Mortimer JT, Scheiner A, Sweeney JD. A spiral nerve cuff electrode for peripheral nerve stimulation. *IEEE Trans Biomed Eng.* 1988; 35:905–16. [PubMed: 3198136]
24. Stein RB, Nichols TR, Jhamandas J, Davis L, Charles D. Stable long-term recordings from cat peripheral nerves. *Brain Res.* 1977; 128:21–38. [PubMed: 871910]
25. Sweeney JD, Mortimer JT. An asymmetric two electrode cuff for generation of unidirectionally propagated action potentials. *IEEE Trans Biomed Eng.* 1986; 33:541–9. [PubMed: 3013759]
26. Kottink AI, Hermens HJ, Nene AV, Tenniglo MJ, Groothuis-Oudshoorn CG, MJ IJ. Therapeutic effect of an implantable peroneal nerve stimulator in subjects with chronic stroke and footdrop: a randomized controlled trial. *Phys Ther.* 2008; 88:437–48. [PubMed: 18218825]
27. Kottink AI, Hermens HJ, Nene AV, et al. A randomized controlled trial of an implantable 2-channel peroneal nerve stimulator on walking speed and activity in poststroke hemiplegia. *Arch Phys Med Rehabil.* 2007; 88:971–8. [PubMed: 17678657]
28. Kottink AI, Tenniglo MJ, de Vries WH, Hermens HJ, Buurke JH. Effects of an implantable two-channel peroneal nerve stimulator versus conventional walking device on spatiotemporal parameters and kinematics of hemiparetic gait. *J Rehabil Med.* 2012; 44:51–7. [PubMed: 22124679]
29. Burridge JH, Taylor PN, Hagan SA, Wood DE, Swain ID. The effects of common peroneal stimulation on the effort and speed of walking: a randomized controlled trial with chronic hemiplegic patients. *Clin Rehabil.* 1997; 11:201–10. [PubMed: 9360032]
30. Dai R, Stein RB, Andrews BJ, James KB, Wieler M. Application of tilt sensors in functional electrical stimulation. *IEEE Trans Rehabil Eng.* 1996; 4:63–72. [PubMed: 8798073]
31. Shimada Y, Ando S, Matsunaga T, et al. Clinical application of acceleration sensor to detect the swing phase of stroke gait in functional electrical stimulation. *Tohoku J Exp Med.* 2005; 207:197–202. [PubMed: 16210830]
32. Lieberman W, Holmquest H, Scot D, Dow M. Functional electrotherapy: Stimulation of the peroneal nerve synchronized with the swing phase of the gait of hemiplegia patients. *Arch Phys Med Rehabil.* 1961; 42:101–5. [PubMed: 13761879]
33. Taylor PN, Burridge JH, Dunkerley AL, et al. Clinical use of the Odstock dropped foot stimulator: its effect on the speed and effort of walking. *Arch Phys Med Rehabil.* 1999; 80:1577–83. [PubMed: 10597809]
34. Stein RB, Everaert DG, Thompson AK, et al. Long-term therapeutic and orthotic effects of a foot drop stimulator on walking performance in progressive and nonprogressive neurological disorders. *Neurorehabil Neural Repair.* 2010; 24:152–67. [PubMed: 19846759]
35. Kottink AI, Oostendorp LJ, Buurke JH, Nene AV, Hermens HJ, MJ IJ. The orthotic effect of functional electrical stimulation on the improvement of walking in stroke patients with a dropped foot: a systematic review. *Artif Organs.* 2004; 28:577–86. [PubMed: 15153151]

36. Sheffler LR, Hennessey MT, Naples GG, Chae J. Improvement in functional ambulation as a therapeutic effect of peroneal nerve stimulation in hemiplegia: two case reports. *Neurorehabil Neural Repair*. 2007; 21:366–9. [PubMed: 17369519]
37. Mann, GEWP.; Swain, ID. Training effects of electrical stimulation and the conventional ankle foot orthosis in the correction of drop foot following stroke; 1st Annual Conference of FESnet 2002; Glasgow, Scotland. 2002;
38. Sabut SK, Sikdar C, Mondal R, Kumar R, Mahadevappa M. Restoration of gait and motor recovery by functional electrical stimulation therapy in persons with stroke. *Disabil Rehabil*. 2010; 32:1594–603. [PubMed: 20210592]
39. Carnstam B, Larsson LE, Prevec TS. Improvement of gait following functional electrical stimulation. I. Investigations on changes in voluntary strength and proprioceptive reflexes. *Scand J Rehabil Med*. 1977; 9:7–13. [PubMed: 302481]
40. Merletti R, Zelaschi F, Latella D, Galli M, Angeli S, Sessa MB. A control study of muscle force recovery in hemiparetic patients during treatment with functional electrical stimulation. *Scand J Rehabil Med*. 1978; 10:147–54. [PubMed: 705282]
41. Yan T, Hui-Chan CW, Li LS. Functional electrical stimulation improves motor recovery of the lower extremity and walking ability of subjects with first acute stroke: a randomized placebo-controlled trial. *Stroke*. 2005; 36:80–5. [PubMed: 15569875]
42. BurrIDGE J, Taylor P, Hagan S, Swain I. Experience of clinical use of the Odstock dropped foot stimulator. *Artif Organs*. 1997; 21:254–60. [PubMed: 9148719]
43. Ring H, Treger I, Gruendlinger L, Hausdorff JM. Neuroprosthesis for footdrop compared with an ankle-foot orthosis: effects on postural control during walking. *J Stroke Cerebrovasc Dis*. 2009; 18:41–7. [PubMed: 19110144]
44. van Swigchem R, van Duijnhoven HJ, den Boer J, Geurts AC, Weerdesteyn V. Effect of peroneal electrical stimulation versus an ankle-foot orthosis on obstacle avoidance ability in people with stroke-related foot drop. *Phys Ther*. 2012; 92:398–406. [PubMed: 22135711]
45. Waters R, McNeal D, Perry J. Experimental correction of footdrop by electrical stimulation of the peroneal nerve. *J Bone Joint Surg*. 1975; 57A:1047–54. [PubMed: 1081538]
46. Kljajic M, Malezic M, Acimovic R, et al. Gait evaluation in hemiparetic patients using subcutaneous peroneal electrical stimulation. *Scand J Rehabil Med*. 1992; 24:121–6. [PubMed: 1411357]
47. Kenney L, Bultstra G, Buschman R, et al. An implantable two channel drop foot stimulator: initial clinical results. *Artif Organs*. 2002; 26:267–70. [PubMed: 11940030]
48. BurrIDGE J, Haugland M, Larsen B, et al. A Phase II study to evaluate the safety and effectiveness of the ActiGait implanted drop-foot stimulator in established hemiplegia. *J Rehabil Med*. In-press.
49. Bogataj U, Gros N, Kljajic M, Acimovic R, Malezic M. The rehabilitation of gait in patients with hemiplegia: a comparison between conventional therapy and multichannel functional electrical stimulation therapy. *Phys Ther*. 1995; 75:490–502. [PubMed: 7770495]
50. Bogataj U, Gros N, Malezic M, Kelih B, Kljajic M, Acimovic R. Restoration of gait during two to three weeks of therapy with multichannel electrical stimulation. *Phys Ther*. 1989; 69:319–27. [PubMed: 2785273]
51. Stanic U, Acimovic-Janezic R, Gros N, Trnkoczy A, Bajd T, Kljajic M. Multichannel electrical stimulation for correction of hemiplegic gait. Methodology and preliminary results. *Scand J Rehabil Med*. 1978; 10:75–92. [PubMed: 307813]
52. Daly JJ, Ruff RL, Haycook K, Strasshofer B, Marsolais EB, Dobos L. Feasibility of gait training for acute stroke patients using FNS with implanted electrodes. *J Neurol Sci*. 2000; 179:103–7. [PubMed: 11054492]
53. Daly JJ, Roenigk K, Holcomb J, et al. A randomized controlled trial of functional neuromuscular stimulation in chronic stroke subjects. *Stroke*. 2006; 37:172–8. Epub 2005 Dec 1. [PubMed: 16322492]
54. Lauer RT, Peckham PH, Kilgore KL, Heetderks WJ. Applications of cortical signals to neuroprosthetic control: a critical review. *IEEE Trans Rehabil Eng*. 2000; 8:205–8. [PubMed: 10896188]

55. Wolpaw JR, Birbaumer N, McFarland DJ, Pfurtscheller G, Vaughan TM. Brain-computer interfaces for communication and control. *Clin Neurophysiol.* 2002; 113:767–91. [PubMed: 12048038]
56. Peckham, PH. Cleveland Functional Electrical Stimulation Center. National Institute of Biomedical Imaging and Bioengineering; 2012. Development of Networked Implantable Neuroprostheses.
57. Sousa CO, Barela JA, Prado-Medeiros CL, Salvini TF, Barela AM. The use of body weight support on ground level: an alternative strategy for gait training of individuals with stroke. *J Neuroeng Rehabil.* 2009; 6:43. [PubMed: 19951435]
58. Sousa CO, Barela JA, Prado-Medeiros CL, Salvini TF, Barela AM. Gait training with partial body weight support during overground walking for individuals with chronic stroke: a pilot study. *J Neuroeng Rehabil.* 2011; 8:48. [PubMed: 21864373]
59. Burgess JK, Weibel GC, Brown DA. Overground walking speed changes when subjected to body weight support conditions for nonimpaired and post stroke individuals. *J Neuroeng Rehabil.* 2010; 7:6. [PubMed: 20149244]
60. Danielsson A, Sunnerhagen KS. Oxygen consumption during treadmill walking with and without body weight support in patients with hemiparesis after stroke and in healthy subjects. *Arch Phys Med Rehabil.* 2000; 81:953–7. [PubMed: 10896011]
61. Hesse S, Konrad M, Uhlenbrock D. Treadmill walking with partial body weight support versus floor walking in hemiparetic subjects. *Arch Phys Med Rehabil.* 1999; 80:421–7. [PubMed: 10206604]
62. Chen G, Patten C. Treadmill training with harness support: selection of parameters for individuals with poststroke hemiparesis. *J Rehabil Res Dev.* 2006; 43:485–98. [PubMed: 17123188]
63. Chen G, Patten C, Kothari DH, Zajac FE. Gait deviations associated with post-stroke hemiparesis: improvement during treadmill walking using weight support, speed, support stiffness, and handrail hold. *Gait Posture.* 2005; 22:57–62. [PubMed: 15996593]
64. 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. [PubMed: 11994808]
65. Aaslund MK, Helbostad JL, Moe-Nilssen R. Familiarisation to body weight supported treadmill training for patients post-stroke. *Gait Posture.* 2011; 34:467–72. [PubMed: 21782442]
66. Behrman AL, Bowden MG, Nair PM. Neuroplasticity after spinal cord injury and training: an emerging paradigm shift in rehabilitation and walking recovery. *Phys Ther.* 2006; 86:1406–25. [PubMed: 17012645]
67. Perez MA, Field-Fote EC, Floeter MK. Patterned sensory stimulation induces plasticity in reciprocal Ia inhibition in humans. *J Neurosci.* 2003; 23:2014–8. [PubMed: 12657659]
68. Frigon A, Rossignol S. Functional plasticity following spinal cord lesions. *Prog Brain Res.* 2006; 157:231–60. [PubMed: 17167915]
69. Scivoletto G, Ivanenko Y, Morganti B, et al. Plasticity of spinal centers in spinal cord injury patients: new concepts for gait evaluation and training. *Neurorehabil Neural Repair.* 2007; 21:358–65. [PubMed: 17353461]
70. Wolpaw JR. The education and re-education of the spinal cord. *Prog Brain Res.* 2006; 157:261–80. [PubMed: 17167916]
71. Wolpaw JR. Spinal cord plasticity in acquisition and maintenance of motor skills. *Acta Physiol (Oxf).* 2007; 189:155–69. [PubMed: 17250566]
72. McCrea DA, Rybak IA. Organization of mammalian locomotor rhythm and pattern generation. *Brain Res Rev.* 2007
73. Dietz V. Spinal cord pattern generators for locomotion. *Clin Neurophysiol.* 2003; 114:1379–89. [PubMed: 12888019]
74. McCrea DA. Spinal circuitry of sensorimotor control of locomotion. *J Physiol.* 2001; 533:41–50. [PubMed: 11351011]
75. Rossignol S, Dubuc R, Gossard JP. Dynamic sensorimotor interactions in locomotion. *Physiol Rev.* 2006; 86:89–154. [PubMed: 16371596]

76. Rossignol S. Plasticity of connections underlying locomotor recovery after central and/or peripheral lesions in the adult mammals. *Philos Trans R Soc Lond B Biol Sci.* 2006; 361:1647–71. [PubMed: 16939980]
77. Rossignol S, Brustein E, Bouyer L, Barthelemy D, Langlet C, Leblond H. Adaptive changes of locomotion after central and peripheral lesions. *Can J Physiol Pharmacol.* 2004; 82:617–27. [PubMed: 15523519]
78. Enzinger C, Dawes H, Johansen-Berg H, et al. Brain activity changes associated with treadmill training after stroke. *Stroke.* 2009; 40:2460–7. [PubMed: 19461018]
79. Miyai I, Suzuki M, Hatakenaka M, Kubota K. Effect of body weight support on cortical activation during gait in patients with stroke. *Exp Brain Res.* 2006; 169:85–91. [PubMed: 16237521]
80. Hesse S, Bertelt C, Jahnke MT, et al. Treadmill training with partial body weight support compared with physiotherapy in nonambulatory hemiparetic patients. *Stroke.* 1995; 26:976–81. [PubMed: 7762049]
81. Visintin M, Barbeau H, Korner-Bitensky N, Mayo NE. A new approach to retrain gait in stroke patients through body weight support and treadmill stimulation. *Stroke.* 1998; 29:1122–8. [PubMed: 9626282]
82. Barbeau H, Visintin M. Optimal outcomes obtained with body-weight support combined with treadmill training in stroke subjects. *Arch Phys Med Rehabil.* 2003; 84:1458–65. [PubMed: 14586912]
83. Sullivan KJ, Brown DA, Klassen T, et al. Effects of task-specific locomotor and strength training in adults who were ambulatory after stroke: results of the STEPS randomized clinical trial. *Phys Ther.* 2007; 87:1580–602. [PubMed: 17895349]
84. Dean CM, Ada L, Bampton J, Morris ME, Katrak PH, Potts S. Treadmill walking with body weight support in subacute non-ambulatory stroke improves walking capacity more than overground walking: a randomised trial. *J Physiother.* 2010; 56:97–103. [PubMed: 20482476]
85. Mulroy SJ, Klassen T, Gronley JK, Eberly VJ, Brown DA, Sullivan KJ. Gait parameters associated with responsiveness to treadmill training with body-weight support after stroke: an exploratory study. *Phys Ther.* 2010; 90:209–23. [PubMed: 20022996]
86. Moseley AM, Stark A, Cameron ID, Pollock A. Treadmill training and body weight support for walking after stroke. *Cochrane Database Syst Rev.* 2005:CD002840. [PubMed: 16235304]
87. Franceschini M, Carda S, Agosti M, Antenucci R, Malgrati D, Cisari C. Walking after stroke: what does treadmill training with body weight support add to overground gait training in patients early after stroke?: a single-blind, randomized, controlled trial. *Stroke.* 2009; 40:3079–85. [PubMed: 19556526]
88. Hoyer E, Jahnsen R, Stanghelle JK, Strand LI. Body weight supported treadmill training versus traditional training in patients dependent on walking assistance after stroke: a randomized controlled trial. *Disabil Rehabil.* 2012; 34:210–9. [PubMed: 21954995]
89. Nilsson L, Carlsson J, Danielsson A, et al. Walking training of patients with hemiparesis at an early stage after stroke: a comparison of walking training on a treadmill with body weight support and walking training on the ground. *Clin Rehabil.* 2001; 15:515–27. [PubMed: 11594641]
90. Duncan PW, Sullivan KJ, Behrman AL, et al. Body-weight-supported treadmill rehabilitation after stroke. *N Engl J Med.* 2011; 364:2026–36. [PubMed: 21612471]
91. Dobkin BH, Duncan PW. Should body weight-supported treadmill training and robotic-assistive steppers for locomotor training trot back to the starting gate? *Neurorehabil Neural Repair.* 2012; 26:308–17. [PubMed: 22412172]
92. Prado-Medeiros CL, Sousa CO, Souza AS, Soares MR, Barela AM, Salvini TF. Effects of the addition of functional electrical stimulation to ground level gait training with body weight support after chronic stroke. *Rev Bras Fisioter.* 2011; 15:436–44. [PubMed: 22031271]
93. Jezernik S, Colombo G, Keller T, Frueh H, Morari M. Robotic orthosis lokomat: a rehabilitation and research tool. *Neuromodulation.* 2003; 6:108–15. [PubMed: 22150969]
94. Sayers SP, Krug J. Robotic gait-assisted therapy in patients with neurological injury. *Mo Med.* 2008; 105:153–8. [PubMed: 18453195]

95. Husemann B, Muller F, Krewer C, Heller S, Koenig E. Effects of locomotion training with assistance of a robot-driven gait orthosis in hemiparetic patients after stroke: a randomized controlled pilot study. *Stroke*. 2007; 38:349–54. [PubMed: 17204680]
96. Hidler J, Hamm LF, Lichy A, Groah SL. Automating activity-based interventions: the role of robotics. *J Rehabil Res Dev*. 2008; 45:337–44. [PubMed: 18566951]
97. Koenig A, Omlin X, Bergmann J, et al. Controlling patient participation during robot-assisted gait training. *J Neuroeng Rehabil*. 2011; 8:14. [PubMed: 21429200]
98. Huang VS, Krakauer JW. Robotic neurorehabilitation: a computational motor learning perspective. *J Neuroeng Rehabil*. 2009; 6:5. [PubMed: 19243614]
99. Colombo R, Sterpi I, Mazzone A, Delconte C, Pisano F. Taking a lesson from patients' recovery strategies to optimize training during robot-aided rehabilitation. *IEEE Trans Neural Syst Rehabil Eng*. 2012; 20:276–85. [PubMed: 22623406]
100. Hussain S, Xie SQ, Liu G. Robot assisted treadmill training: mechanisms and training strategies. *Med Eng Phys*. 2011; 33:527–33. [PubMed: 21216650]
101. Conesa L, Costa U, Morales E, et al. An observational report of intensive robotic and manual gait training in sub-acute stroke. *J Neuroeng Rehabil*. 2012; 9:13. [PubMed: 22329866]
102. Wu M, Landry JM, Yen SC, Schmit BD, Hornby TG, Rafferty M. A novel cable-driven robotic training improves locomotor function in individuals post-stroke. *Conf Proc IEEE Eng Med Biol Soc*. 2011; 2011:8539–42. [PubMed: 22256331]
103. Westlake KP, Patten C. Pilot study of Lokomat versus manual-assisted treadmill training for locomotor recovery post-stroke. *J Neuroeng Rehabil*. 2009; 6:18. [PubMed: 19523207]
104. 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. [PubMed: 17476001]
105. Coenen P, van Werven G, van Nunen MP, Van Dieen JH, Gerrits KH, Janssen TW. Robot-assisted walking vs overground walking in stroke patients: an evaluation of muscle activity. *J Rehabil Med*. 2012; 44:331–7. [PubMed: 22453772]
106. Tefertiller C, Pharo B, Evans N, Winchester P. Efficacy of rehabilitation robotics for walking training in neurological disorders: a review. *J Rehabil Res Dev*. 2011; 48:387–416. [PubMed: 21674390]
107. Hesse S, Tomelleri C, Bardeleben A, Werner C, Waldner A. Robot-assisted practice of gait and stair climbing in nonambulatory stroke patients. *J Rehabil Res Dev*. 2012; 49:613–22. [PubMed: 22773263]
108. Morone G, Bragoni M, Iosa M, et al. Who may benefit from robotic-assisted gait training? A randomized clinical trial in patients with subacute stroke. *Neurorehabil Neural Repair*. 2011; 25:636–44. [PubMed: 21444654]
109. Morone G, Iosa M, Bragoni M, et al. Who may have durable benefit from robotic gait training?: a 2-year follow-up randomized controlled trial in patients with subacute stroke. *Stroke*. 2012; 43:1140–2. [PubMed: 22180255]
110. Schwartz I, Sajin A, Fisher I, et al. The effectiveness of locomotor therapy using robotic-assisted gait training in subacute stroke patients: a randomized controlled trial. *PM R*. 2009; 1:516–23. [PubMed: 19627940]
111. Chang WH, Kim MS, Huh JP, Lee PK, Kim YH. Effects of robot-assisted gait training on cardiopulmonary fitness in subacute stroke patients: a randomized controlled study. *Neurorehabil Neural Repair*. 2012; 26:318–24. [PubMed: 22086903]
112. Mehrholz J, Werner C, Kugler J, Pohl M. Electromechanical-assisted training for walking after stroke. *Cochrane Database Syst Rev*. 2007; CD006185. [PubMed: 17943893]
113. Fisher S, Lucas L, Thrasher TA. Robot-assisted gait training for patients with hemiparesis due to stroke. *Top Stroke Rehabil*. 2011; 18:269–76. [PubMed: 21642064]
114. Bogey R, Hornby GT. Gait training strategies utilized in poststroke rehabilitation: are we really making a difference? *Top Stroke Rehabil*. 2007; 14:1–8. [PubMed: 18171655]
115. Hidler J, Nichols D, Pelliccio M, et al. Multicenter randomized clinical trial evaluating the effectiveness of the Lokomat in subacute stroke. *Neurorehabil Neural Repair*. 2009; 23:5–13. [PubMed: 19109447]

116. Hornby TG, Campbell DD, Kahn JH, Demott T, Moore JL, Roth HR. Enhanced gait-related improvements after therapist-versus robotic-assisted locomotor training in subjects with chronic stroke: a randomized controlled study. *Stroke*. 2008; 39:1786–92. [PubMed: 18467648]
117. Lewek MD, Cruz TH, Moore JL, Roth HR, Dhaer YY, Hornby TG. Allowing intralimb kinematic variability during locomotor training poststroke improves kinematic consistency: a subgroup analysis from a randomized clinical trial. *Phys Ther*. 2009; 89:829–39. [PubMed: 19520734]
118. Forrester LW, Roy A, Krebs HI, Macko RF. Ankle training with a robotic device improves hemiparetic gait after a stroke. *Neurorehabil Neural Repair*. 2011; 25:369–77. [PubMed: 21115945]
119. Kim SH, Banala SK, Brackbill EA, Agrawal SK, Krishnamoorthy V, Scholz JP. Robot-assisted modifications of gait in healthy individuals. *Exp Brain Res*. 2010; 202:809–24. [PubMed: 20186402]
120. Mirelman A, Patrissi BL, Bonato P, Deutsch JE. Effects of virtual reality training on gait biomechanics of individuals post-stroke. *Gait Posture*. 2010; 31:433–7. [PubMed: 20189810]
121. Mirelman A, Bonato P, Deutsch JE. Effects of training with a robot-virtual reality system compared with a robot alone on the gait of individuals after stroke. *Stroke*. 2009; 40:169–74. [PubMed: 18988916]
122. Wellner M, Thuring T, Smajic E, von Zitzewitz J, Duschau-Wicke A, Riener R. Obstacle crossing in a virtual environment with the rehabilitation gait robot LOKOMAT. *Stud Health Technol Inform*. 2007; 125:497–9. [PubMed: 17377335]

Key points

- Post-stroke gait training interventions may be either therapeutic resulting in enhanced motor recovery or compensatory whereby assistance or substitution for neurological deficits results in improved functional performance.
- Functional electrical stimulation, body-weight supported treadmill training, and robotic-assisted gait training are examples of post-stroke gait training therapies.
- Post-stroke gait training therapies are predicated on activity-dependent neuroplasticity which is the concept that cortical reorganization following CNS injury may be induced by repetitive, skilled, and cognitively engaging active movement.
- Additional research is necessary to determine if specific technology-enhanced gait training methods are superior to conventional gait training methods.

Figure 1.
The Odstock Dropped Foot Stimulator®. Courtesy of Odstock Medical Limited, The National Clinical FES Centre, Salisbury, UK.

Figure 2.
The Bioness L300® Footdrop System. Courtesy of Bioness Inc., Valencia, CA.

Figure 3.
The WalkAide® System. Courtesy of Innovative Neurotronics, Austin, TX.