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Powered lower limb orthoses for gait rehabilitation

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Abstract

Bodyweight supported treadmill training has become a prominent gait rehabilitation method in leading rehabilitation centers. This type of locomotor training has many functional benefits but the labor costs are considerable. To reduce therapist effort, several groups have developed large robotic devices for assisting treadmill stepping. A complementary approach that has not been adequately explored is to use powered lower limb orthoses for locomotor training. Recent advances in robotic technology have made lightweight powered orthoses feasible and practical. An advantage to using powered orthoses as rehabilitation aids is they allow practice starting, turning, stopping, and avoiding obstacles during overground walking.

Keywords

locomotion; exoskeleton; locomotor training; bodyweight support; robotics

Introduction

Rehabilitation after neurological injury relies on three principles of motor learning. Practice is the first principle. All other things being equal, more learning will occur with more practice[1]. Specificity is the second principle. The best way to improve performance of a motor task is to execute that specific motor task[2]. Effort is the third principle. Individuals need to maintain a high degree of participation and involvement to facilitate motor learning[3, 4]. These three principles are critical to promoting activity-dependent plasticity (i.e. altering the efficacy and excitation patterns of neural pathways by activating those pathways)[5]. With regards to neurological rehabilitation, it is important to emphasize that plasticity occurs in neural pathways that are *active*. Thus, maximizing neuromuscular recruitment during task-specific practice increases the potential for plasticity. A recent study examining upper limb rehabilitation after stroke[6] has clearly demonstrated this premise. Passive arm movements induced by a robotic manipulandum provided little functional benefit to subjects with partial paralysis. In contrast, active arm movements that were resisted by the robotic manipulandum resulted in improved motor ability.

The most prominent method of gait rehabilitation in current research is bodyweight supported treadmill training. This is a relatively new technique that originated from basic science research on the neural control of vertebrate locomotion. Spinalized cats can be trained to walk on a treadmill with partial unweighting of their hindlimbs[7-9]. Locomotor recovery with stepping

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practice on a treadmill is much greater than that ascribed to spontaneous recovery alone[10]. Based on these observations of spinal cats, a number of research teams around the world began testing similar treadmill stepping paradigms in humans[11-14]. Typically, neurologically impaired subjects wear harnesses that support some of their bodyweight as therapists manually assist their legs through the stepping motion on a treadmill (Figure 1).

The neural mechanisms involved in bodyweight supported treadmill training are not entirely understood but sensory stimulation appears to be critical. Motor recovery could result from formation of new neural pathways or modification of existing neural pathways[15-17]. It is likely that both contribute to some degree. The spinal cord and brain can each undergo considerable activity-dependent plasticity. Current scientific evidence does not indicate if one or the other is more prominent in the functional recovery of human walking, but optimal recovery would require neural modifications in both locations. One observation that does appear consistently is that appropriate sensory stimulation is required to instigate neural changes for improved functional ability[18, 19]. As such, proponents of bodyweight supported treadmill training recommend that certain "rules of spinal locomotion" be followed to maximize neurological recovery[20, 21]. Some of these rules include ensuring hip extension at the end of stance phase, adequate weight bearing on the stance limb, and lateral weight shifting during the double support phase. However, there is not universal agreement on ideal training parameters for bodyweight supported treadmill training[22]. For example, treadmill speed, stepping frequency, bodyweight support level, and amount of mechanical assistance are parameters that can greatly vary from therapist to therapist.

Of greatest importance for clinicians and patients are the functional improvements that occur with locomotor training. Several studies have demonstrated that treadmill stepping with partial bodyweight support can improve walking in patients with spinal cord injury[17, 23-26]. The most extensive study published to date found that 80% of wheelchair bound patients with chronic incomplete spinal cord injury gained functional walking ability after training[20, 27]. A multi-center clinical trial of bodyweight supported treadmill training in acute spinal cord injury subjects recently ended[28], but detailed results have not been published yet. Given the heterogeneity of spinal cord injury subjects and variety of training parameters that can vary across therapists or centers, it is unrealistic to expect that all clinical trials of bodyweight supported treadmill training would produce similar results. Optimizing gait rehabilitation with this therapy will require considerable more investigation into how different training parameters contribute to motor recovery given different patient characteristics.

If we consider bodyweight supported treadmill training in view of the three motor learning principles presented earlier, we may gain insight into how this treatment can be improved. There is a clear limitation of the therapy in the first principle (i.e., practice). Two or more therapists are required to assist with leg motion and stabilize the torso[23]. In addition, the amount of treadmill training is often limited by the endurance of the trainers, not the endurance of the patient. Both of these factors place a strain on limited clinical resources, thereby reducing the amount of practice that is possible. Bodyweight supported treadmill training clearly addresses the second principle of specificity, but there are some restrictions. The debate over transfer of treadmill stepping to overground walking appears to be a minor issue[20, 27]. On the other hand, locomotor tasks such as starting, stopping, turning, and avoiding obstacles are not represented in most bodyweight supported treadmill training paradigms. Another form of locomotor training that can incorporate these additional locomotor tasks may provide further improvements in functional ability. The third principle, effort, depends at least partially on the parameters chosen by the therapist. Both clinically complete and clinically incomplete spinal cord injury subjects can demonstrate robust neuromuscular recruitment during treadmill stepping with partial bodyweight support[12, 13, 29, 30]. Two important training parameters that have been shown to alter neuromuscular recruitment are bodyweight support level[29] and treadmill speed[31]. A third parameter that has been controversial is the amount of manual assistance.

For patients with incomplete spinal cord injury and limited walking ability, some clinicians believe that it is best to let the patient step on the treadmill completely under his/her power. The rationale is that therapist assistance may be detrimental to neuromuscular recruitment, and thus activity-dependent plasticity, because it promotes passivity by the patient. However, recent evidence indicates that subjects with incomplete spinal cord injury do not demonstrate reduced muscle activation when provided with manual assistance during treadmill stepping[32]. Indeed, if there is a difference in neuromuscular recruitment between conditions, manual assistance of the lower limbs during bodyweight supported treadmill stepping actually increases electromyography amplitudes compared to no assistance (Figure 2). Thus, the fear that manual assistance reduces neuromuscular recruitment and promotes passivity in patients with limited walking ability appears to be unfounded.

Based on the limitations of bodyweight supported treadmill training presented above, it would seem helpful to have a complementary form of locomotor training that requires less therapist labor and incorporates a wide range of locomotor tasks. We propose that powered lower limb orthoses can serve this role as rehabilitation aids. Traditionally, lower limb orthoses have been passive braces that either limit the range of joint motion or prevent joint motion entirely. Their purpose was to compensate for lost mechanical function (i.e., assistive technology). Alternatively, powered lower limb orthoses could be used as a tool to facilitate functional motor recovery by allowing a patient to practice walking in clinical setting (i.e., rehabilitation). The key difference is that the end goal is to increase the patient's own functional ability when they are not wearing the orthoses. To succeed as rehabilitation aids, however, orthoses should be powered so that they promote appropriate gait dynamics. Fortunately, robotic technology has greatly advanced in the last twenty years. Increased computer processor speed, more robust control approaches, and lightweight actuators and sensors have all contributed. Lower limb prosthetics have clearly benefited from the advanced technology. The Otto Bock C-Leg©, an above knee lower limb prosthesis with a computer processor to control knee impedance, is a prime example[33]. The near future will see even more advanced robotic technology that can be incorporated into powered lower limb orthoses for locomotor training.

Robotic devices for treadmill stepping

Because bodyweight supported treadmill training has high therapist labor requirements, research groups around the world have developed a host of robotic devices to assist treadmill stepping[34, 35]. The purpose of these machines is to replace therapist manual assistance, increasing the amount of stepping practice while decreasing therapist effort. Two of the devices have undergone substantial testing with neurologically impaired subjects. The Lokomat®, developed by Hocoma, consists of a robotic lower limb interface that attaches to a treadmill frame and body weight support system[36]. The patient's legs are strapped into an adjustable aluminum frame that provides powered assistance at the hip and knee while the patient steps on a treadmill. A therapist can monitor the system and adjust assistance as necessary. The Lokomat® has been shown to be effective in improving walking ability in individuals with incomplete spinal cord injury[37, 38]. Another machine that does not work in conjunction with a treadmill but has the same primary function of assisting locomotor training with partial bodyweight support is the Mechanized Gait Trainer[39]. The Mechanized Gait Trainer uses a crank and rocker gear system, providing limb motion similar to that occurring on an elliptical trainer. Results with this device indicate it is at least as successful as manually-assisted bodyweight supported treadmill training in restoring gait ability after stroke[40].

While these large robotic devices address the drawback of therapist labor requirements, they are not likely to be the universal solution for all patients. They do not allow users to practice walking overground, turning, or avoiding obstacles. Severely impaired subjects clearly profit from the repetitive steady speed stepping induced by the devices, but less impaired subjects may benefit from more challenging locomotor tasks. Another important aspect of the robotic stepping devices is that they do not provide active assistance at the ankle joint. They rely on assistance at the hip and knee joints to induce the stepping pattern. This may be a key factor for less impaired subjects because the ankle provides more power than either the hip or knee during normal walking[41] (Figure 3). If patients cannot practice a gait pattern that includes sufficient ankle push-off at the end of stance, they are likely to learn a compensatory gait rather than a normal gait. A consequence of inadequate ankle push-off would be a gait pattern with substantially greater metabolic cost[42]. It may be extremely beneficial for spinal cord injury patients to practice walking with active ankle assistance if they are to develop normal walking dynamics.

Powered Orthoses as Assistive Technology

Engineers have long sought to build powered orthoses that could replace lost motor function of individuals with neurological impairments. Some of the first working robotic orthoses date back to the mid-1970s[43-46]. Miomir Vukobratovic in Yugoslavia created one of the most advanced models of the time period (Figure 4A). His device used pneumatic actuators at the hip, knee, and ankle to provide assistance in the frontal and sagittal planes[43, 44]. Clinical tests on a paraplegic patient showed that the orthosis allowed a slow walk with support from railings. At a similar time, Ali Seireg at the University of Wisconsin developed a hydraulic orthosis with a dual axis hip, dual axis ankles and single axis knees[47]. A neurologically intact subject wore the orthosis for several hours, demonstrating it could assist walking comfortably for extended time periods. Seireg's powered orthosis is now a permanent exhibit in the Wellcome Museum of the History of Medicine, Science Museum, in London. More recently, Ruthenberg et al. at Michigan Technological University[48] and Belforte et al. in Italy[49] developed their versions of powered orthoses. All of these devices underwent testing on human subjects, but they did not achieve sufficient utility to be produced on a wider scale.

With the arrival of better and smaller actuators, sensors, and computer processors, powered orthoses will soon become a reality in the clinical community. One academic laboratory focusing on integrating new technology into orthotics and prosthetics is the Biomechatronics Laboratory at the MIT Media Laboratory. The director, Hugh Herr, has developed a computer controlled above-knee prosthesis[50] to rival the Otto Bock C-Leg. It is currently being sold commercially by Ossur. The lab also developed a prototype powered ankle-foot orthosis intended to assist patients with drop foot (Figure 4B)[51]. Another academic laboratory that is leading the way in developing powered orthoses for assistive technology is the Cybernics Laboratory at the University of Tsukuba in Japan. Director Yoshiyuki Sankai and his laboratory members have developed an electromechanical powered orthosis called HAL (Hybrid Assistive Limb) (Figure 4C). It includes four rotational motors that assist knee and hip joints on both lower limbs based on feedback from force sensors and muscle activation amplitudes[52-54]. The lab has recently announced they plan on selling commercially available versions of HAL by the end of 2005 at a price of less than $20,000 USD[55]. There have been a few companies pursuing powered lower limb orthoses for assistive technology, such as Yobotics, Inc.[56], but most current research is being conducted in academic laboratories.

There is another class of powered orthoses that are intended to increase human motor abilities over and above normal levels. These human performance augmentation devices provide superhuman motor function to neurologically intact individuals. They have also been referred to as robotic exoskeletons. In industrial settings where heavy lifting or long hours on the feet are required, a device that could augment strength or increase endurance would be very helpful. Civil servants such as fire and police units could also benefit from increased strength in emergency situations. The Defense Advanced Research Projects Agency (DARPA) in the United States has funded much of the recent research on robotic exoskeletons for human performance augmentation. The DARPA program hopes to yield devices that can increase the speed, strength, and endurance of soldiers in combat environments (Figure 5A). Two groups are currently developing working exoskeletons financed by DARPA. One group at Sarcos Inc. is led by Stephen Jacobsen (Figure 5B)[57]. Homayoon Kazerooni at UC Berkeley leads the other group. Their prototype is called BLEEX (Berkeley Lower Extremity Exoskeleton) (Figure 5C)[58]. While the exact devices created by these research groups may not be readily used as assistive technology, it is likely that their research will result in spin-off technology that can later be incorporated into powered orthoses for neurologically impaired humans.

Powered Orthoses as Rehabilitation Aids

A major obstacle to the creation of robotic devices that can be used in multiple environments is energy density. That is, to make the devices portable, the actuators and power storage (e.g., batteries) have to be lightweight while still providing many hours of use. In the past, motors strong enough to assist human locomotion have been extremely bulky and the batteries required a massive backpack. The creators of HAL have been able to use enhanced electromechanical motors and batteries, greatly reducing the mass of their powered orthosis. In contrast, the DARPA funded researchers have resorted to novel combustion engines to produce high power outputs for extended durations.

Powered orthoses for gait rehabilitation do not face an energy density problem. They are not meant to be portable or provide long-term functional replacement. Their purpose is to facilitate motor learning by encouraging proper gait dynamics during locomotor training. As a result, computer processors, energy supplies, and even actuators do not have to be on the orthosis or user. Electric, hydraulic, or pneumatic energy could be supplied through a tether that includes cables connected to a desktop computer.

Another problem encountered by powered orthoses for assistive technology and human performance augmentation is control reliability. Control strategies and algorithms for portable robotic devices must be extremely robust and safe for human interaction. Most developers of robotic exoskeletons tend to favor a simple control method based on force sensors[56, 59] because there is less chance of the computer processor receiving noisy feedback. Sankai and colleagues have used a mix of different feedback signals for control of HAL, including force sensors and electromyography. A potential drawback of electromyography for portable robotic control is that electrodes can be fairly fragile in real world environments.

Powered orthoses for gait rehabilitation have many options to solve control problems because they are only used in the clinic or laboratory. Digital control processing can be done on a powerful computer located off of the user. This could allow a therapist to choose from a library of possible control paradigms and even have real-time control over the magnitude and timing of the robotic assistance during gait practice. If a patient does not respond to one method of control, the therapist could easily change methods. The computer could also record robotic assistance and gait dynamics, allowing therapists to track improvement of the patient. Therapists could progressively decrease orthosis assistance over time to enforce active patient participation. Several of the research groups developing large robotic devices for locomotor training are currently attempting to implement many of these ideas in their devices[60-62].

Pneumatically Powered Orthoses at the University of Michigan

In the University of Michigan Human Neuromechanics Laboratory, we have developed pneumatically powered orthoses for assisting human walking (Figure 6)[63-65]. Ankle-foot orthoses and knee-ankle-foot orthoses are made from a combination of carbon fiber and polypropylene and are custom fit to each subject. Steel hinge joints allow sagittal plane movement while artificial pneumatic muscles provide flexion and extension torque. The advantages of artificial pneumatic muscles are high power outputs, low actuator mass, and natural compliance. The artificial muscle is made from an expandable rubber bladder inside braided polyester sleeving. When the bladder is inflated, the sleeving constrains expansion of the bladder so that the pneumatic muscle shortens and/or produces force if coupled to mechanical resistance. The mechanical properties of artificial pneumatic muscles have been described in detail[66]. The powered orthoses are comfortable, lightweight and allow movement through a normal range of motion during walking. With this type of powered orthosis, a patient could walk on a treadmill or could practice overground locomotor tasks such as starting, stopping, turning, and obstacle negotiation.

In studies of locomotor adaptation on neurologically intact subjects, we tested several different control methods[67]. Some of these include proportional myoelectric control (where orthosis torque is nonlinearly related to electromyography amplitude), foot switch control (where orthosis torque is either on or off depending on the phase of the gait cycle), and push-button control (where orthosis torque is nonlinearly related to the displacement of a thumb plunger held by the user). When activated under foot switch control, the simplest control method, the powered ankle-foot orthosis can generate ~60% of normal ankle plantar flexor torque during stance and can perform ~70% of the plantar flexor work done during normal walking[63].

Powered orthoses for gait rehabilitation face the same question about neuromuscular recruitment that we addressed earlier for manual assistance. Robotic assistance may promote patient passivity because the patients come to rely on the powered orthosis rather than putting forth maximum effort. To address this possibility, we tested the effects of robotic plantar flexion assistance on muscle activation and joint kinematics in incomplete spinal cord injury subjects[67]. Spinal cord injury subjects often do not have appropriately timed muscle activity; so handheld control switches activated the powered orthoses (Figure 6). Subjects walked on a treadmill with a harness providing partial bodyweight support to facilitate stepping. They completed four conditions: without the orthoses, with the orthoses turned off, with the orthoses active under therapist control, and with the orthoses active under subject control. If robotic assistance promotes passivity, then muscle activation amplitudes of the plantar flexors (i.e. soleus, medial gastrocnemius, and lateral gastrocnemius) would have decreased when the orthoses were active. Contrary to this prediction, robotic assistance at the ankle joint did not reduce soleus or gastrocnemius electromyography amplitude[67] (Figure 7). In addition, the added torque at the ankle joint provided increased plantar flexion at the end of the stance phase, promoting more normal gait dynamics. The findings from this study suggest that powered orthoses, similar to manual assistance, do not cause patients to become passive and reduce their muscle activation amplitudes. Manual or robotic assistance during gait training results in better gait kinematics. This may lead to more appropriate sensory feedback and increase motor output of the spinal locomotor networks. Future studies need to examine long-term training to determine if stepping practice with powered orthoses can bring about improvements in functional mobility.

Conclusions

Advances in robotic technology have led to the development of several powered lower limb orthoses. Clinical researchers need to take advantage of these new devices to determine if they can be helpful for gait rehabilitation after neurological injury. Theoretically, they should be able to promote more normal gait dynamics during locomotor training while reducing therapist labor. Powered orthoses may also prove valuable in allowing patients to practice diverse locomotor tasks that are more characteristic to normal ambulation in real world environments.

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Figure 1.
Bodyweight supported treadmill training. Physical therapists can administer body weight supported treadmill training in the clinic. The patient's body weight is partially supported by way of a modified parachute harness worn on the trunk. Two therapists manually assist the motion of the patient's legs through a natural gait pattern. A third therapist stands behind the patient and provides trunk support. Source: The New York Times, Science News, 9/21/99. Permission to reprint photo from Michael Tweed.

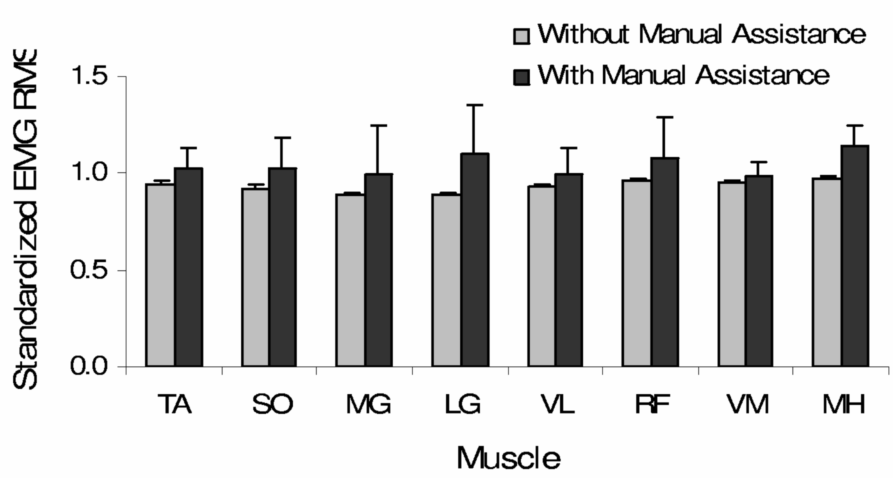

Figure 2.

Electromyography amplitude (root mean square, RMS) with and without manual assistance in subjects with incomplete spinal cord injury. Four subjects with incomplete spinal cord injury walked on a treadmill at 0.36 m/s with bodyweight support, with and without manual assistance. While walking under the two experimental conditions, electromyography data were recorded from 8 muscles (tibialis anterior, TA; soleus, SO; medial gastrocnemius, MG; lateral gastrocnemius, LG; vastus lateralis, VL; vastus medialis, VM; rectus femoris, RF; and medial hamstring, MH). Electromyography RMS values were averaged and standardized to the highest RMS value. Error bars indicate standard error. Electromyography amplitudes were greater in all muscles with manual assistance, but the difference was not statistically significant ($p > 0.3$). Source: Original figure from the Human Neuromechanics Laboratory at the University of Michigan.

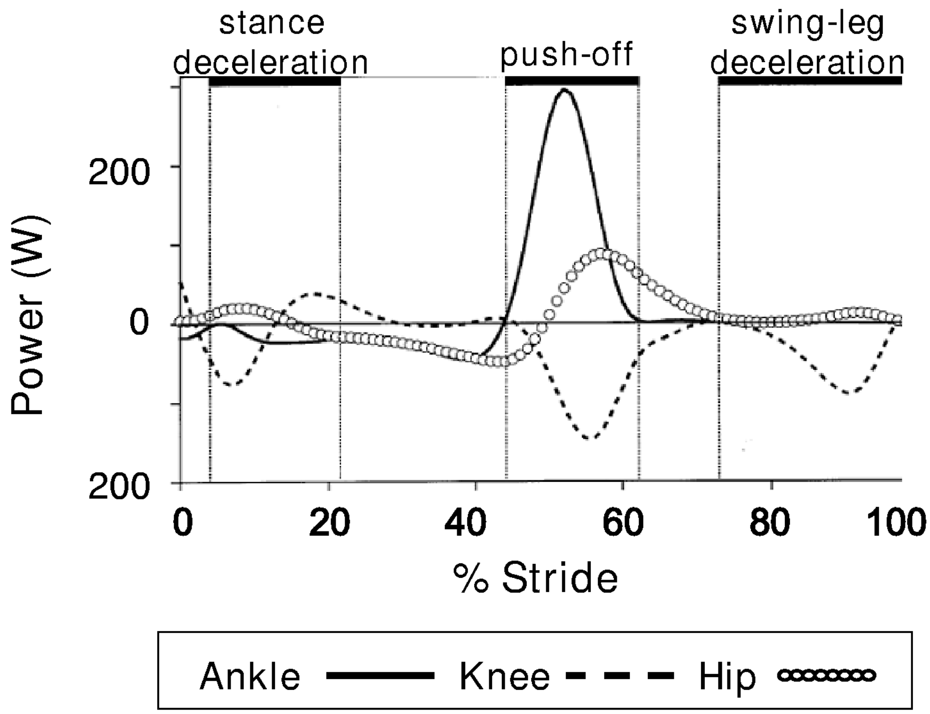

Figure 3.

Ankle, knee, and hip joint powers over the stride cycle for normal human walking. Heel strike is at 0% and again at 100%. Toe off occurs at ~ 60%. The majority of the joint power comes from the ankle joint just before toe off. Source: Meinders et al. *Scand J Rehab Med* 30: 39-46, 1998. Permission to reprint fromTaylor and Francis Publishing.

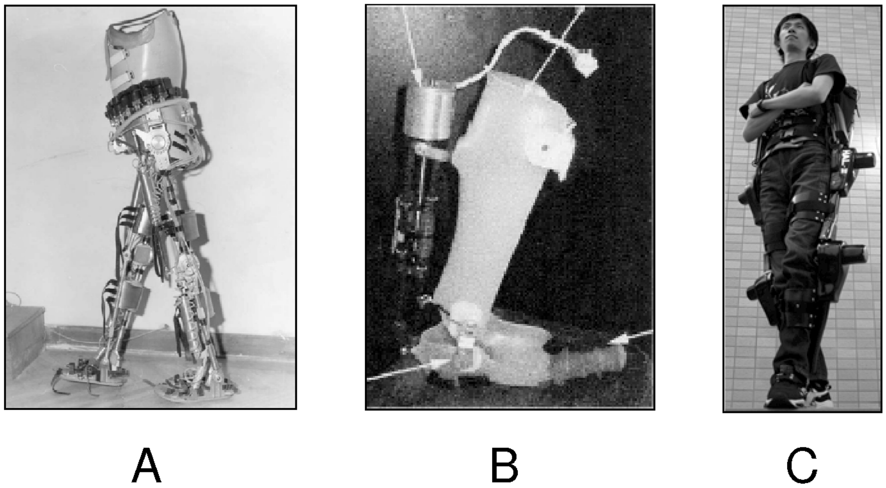

Figure 4.
Powered orthoses as assistive technology. A. The exoskeleton developed by Vukobratovic in Yugosalvia in the1970s. B. Blaya and Herr's powered ankle-foot-orthosis for drop foot correction. C. The hybrid assistive limb (HAL) is currently under development by engineers in the Cybernetics Laboratory at the University of Tsukuba in Japan. Source: A. Vukobratovic et al., *Med Biol Eng*, January, 1974. Permission to reprint from Peter Peregrinus Ltd. B. Blaya et al., *IEEE Trans Neur Sys Eng*, 12(1), 24-31, 2004. Permission to reprint from IEEE. C. Original photograph from Prof. Sankai, University of Tsukuba / Cyberdyne Inc. Permission to reprint from Yoshiyuki Sankai, University of Tsukuba. / Cyberdyne Inc.

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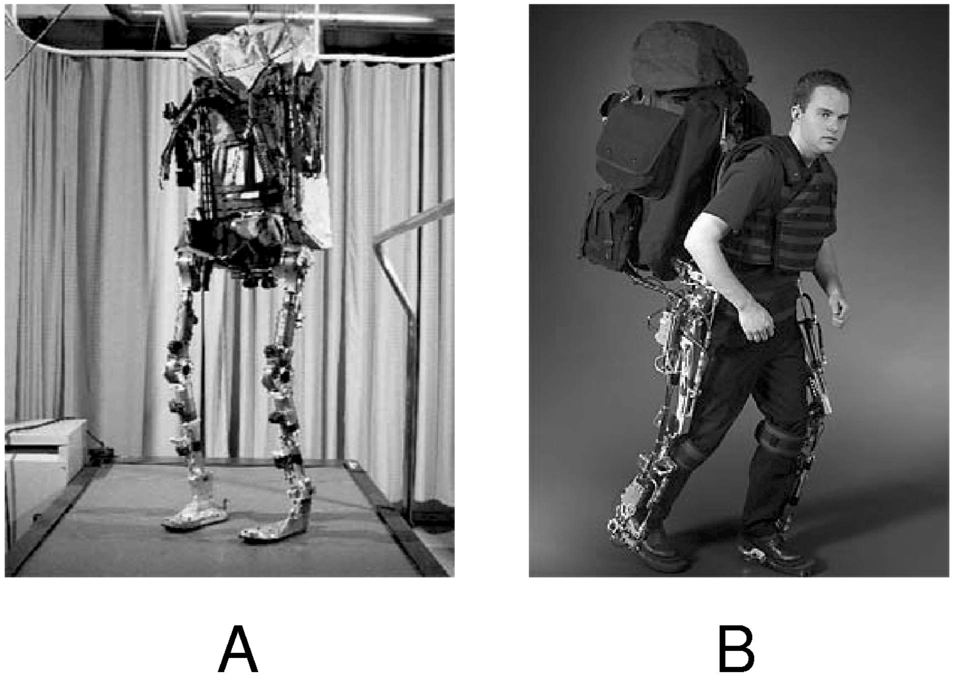
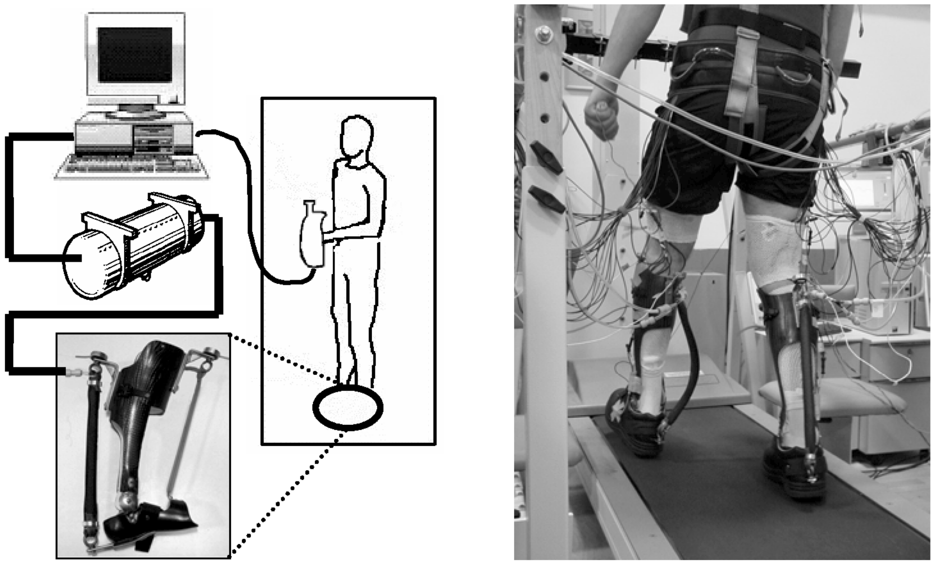


Figure 5.
Powered orthoses for power augmentation. A. The Sarcos protoype is being developed under the direction of Stephen Jacobsen with funding from the Defense Advanced Research Projects Agency (DARPA). B. BLEEX, the Berkeley Lower Extremity Exoskeleton, is under development in Homayoon Kazerooni's Laboratory at the University of California Berkeley, also with funding from DARPA. Source: A. *Technology Review*, p.73, July/August, 2004. Permission to reprint from MIT Technology Review. B. website: bleex.me.berkeley.edu/ bleex.htm. Permission to reprint from Professor H. Kazerooni, Robotics and Human Engineering Laboratory, University of California at Berkeley.



A B

Figure 6.
Pneumatically powered orthoses at the University of Michigan. A. The patient controls the timing of assistance with push buttons in each hand through an algorithm programmed on a remote computer. The computer commands airflow into and out of the pneumatic actuators attached to the orthoses, producing assistive torque at the ankle joint. B. A patient uses the push button controllers to assist walking on a treadmill. Source: Original figure from the Human Neuromechanics Laboratory at the University of Michigan.

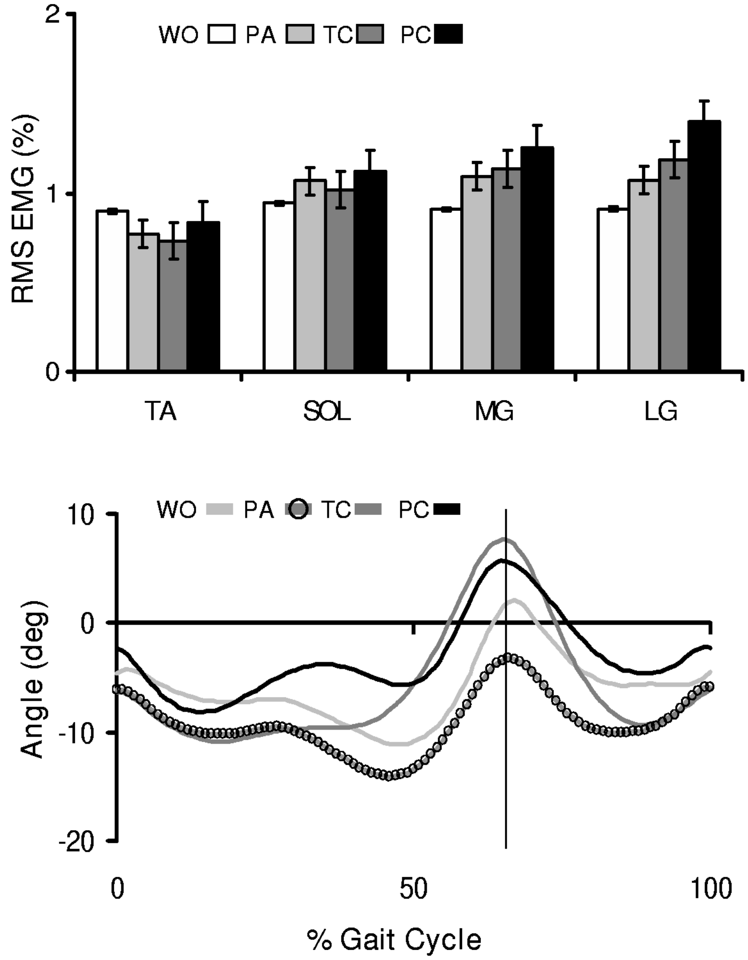


Figure 7.
Muscle activation and kinematic patterns for gait training with powered orthoses. Data are averaged for six incomplete spinal cord subjects (ASIA C-D) walking on a treadmill with partial body weight support (0.54 m/s). Subjects walked under four conditions: without the orthoses (WO), wearing passive orthoses (PA), wearing active orthoses under therapist control (TC) and wearing active orthoses under patient control (PC). TOP: Normalized root mean square EMG of tibialis anterior (TA), soleus (SOL), medial gastrocnemius (MG) and lateral gastrocnemius (LG). BOTTOM: Mean ankle angle during the gait cycle. Plantar flexion is positive. Source: Original figure from the Human Neuromechanics Laboratory at the University of Michigan.