Robotic Devices for Overground Gait and Balance Training

22

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Abstract

In recent years, we have seen the emergence of robotic technologies that focus on assisting individuals during overground gait and balance therapy following neurological injury and diseases. These devices range in complexity, depending on the type of assistance they provide. For example, at the single joint level, exoskeletons are now being used to supplement limb propulsion as a means of compensating for weakness and poor coordination. At the whole-body level, active body-weight support systems are being used to enhance postural stability as well as compensate for bilateral weakness during gait and balance training.

One of the key aspects of using robots that support overground gait and balance training is that they allow individuals the ability to practice the types of activities they will need to be competent in before returning to their home and into the community. The ability to walk overground, practice standing up and sitting down, and other functional tasks are critical components of achieving functional independence yet are often difficult to safely practice for patients with significant levels of impairment. Not only

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is the patient at risk for injury but so too is the therapist. The integration of robotic technologies into neurorehabilitation can play a critical role in the safe and effective delivery of gait and balance therapy.

The focus of this chapter is to present some of the newest robotic technologies that support overground gait and balance training, discuss the potential advantages and disadvantages of each, and provide a framework for how each may be useful in the clinical setting. Since the area of rehabilitation robotics is quickly expanding with many devices being developed in laboratories around the world, it is not possible for us to detail every technology. Instead, we will highlight a few of the devices and use them for providing a rationale for their usefulness in neurorehabilitation.

Keywords
Robotics • Rehabilitation • Gait • Waling • Stroke • Spinal cord injury

22.1 Lower Extremity Exoskeletons

22.1.1 Ankle Robotic Technologies

Following neurological injuries such as stroke and traumatic brain injury, individuals often experience significant weakness and the loss of coordination in their lower extremities which leads to compromised walking ability and increased risks for falls [1–3] (see [4] for a review). Of particular interest in the lower extremities is the ankle, since ankle moments make up nearly 40% of the total positive work generated in gait [5]. Compensating for ankle weakness could potentially increase limb propulsion and consequently improve walking ability.

One therapeutic approach to ameliorating ankle impairments is by using an ankle robot. For example, the AnkleBOT, developed by Krebs and colleagues at MIT [6], is a 2-degree-of-freedom robot that actuates the ankle in both flexion and extension as well as inversion–eversion. The device, as shown in Fig. 22.1, weighs 3.6 kg and is mounted to a knee brace connected to the distal thigh and proximal shank. Moving the weight of the device higher on the individual's leg helps to reduce the inertial effects of moving the device through swing. The AnkleBOT is capable of generating 23 Nm of torque in flexion–extension and 15 Nm of torque in inversion–eversion. The device is programmed to only provide active assistance to the individual if they deviate too far from a reference trajectory, often derived from individuals with no gait disorders. As long as the user remains near this trajectory, the robot provides no assistance. However, as the user moves further away from this trajectory, the magnitude of assistance the AnkleBOT provides will increase.

Preliminary studies with the AnkleBOT have sought to determine whether the added inertia and friction of the device would negatively influence gait parameters (e.g., step length, cadence), interlimb symmetry, and lower extremity joint kinematics in subjects with lower extremity impairments [7]. Ten chronic stroke survivors walked overground and on a treadmill without any assistive devices and with the AnkleBOT turned off. It was found that when subjects walked with the AnkleBOT, there were no significant changes in spatiotemporal gait parameters or interlimb symmetry; however, the presence of the robot did decrease the nonparetic knee peak flexion on the treadmill and paretic peak dorsiflexion overground. While the presence of the AnkleBOT did not appear to adversely influence the gait patterns of the subjects tested in this study, it should be noted that the authors did not report on the impairment level of the participants in their study. Further testing is necessary to determine if all subjects, including those with significant impairments, can tolerate the added inertia and friction of the device. To date, there are no clinical studies examining the effects of overground gait

Fig. 22.1 AnkleBOT robot provides subjects active assistance in flexion–extension and inversion–eversion as they walk overground or on a treadmill

Fig. 22.2 Pneumatically actuated ankle device being tested to assist with limb propulsion [9]

training with the AnkleBOT, only in seated position [8]. There, a sample of convenience of eight chronic stroke patients trained for 6 weeks, three times per week, with a visually evoked and guided video game. This uncontrolled study demonstrated changes of 20% in self-selected gait speed and other spatiotemporal gait parameters, suggesting that there is potential to employ this kind of device even in a non-task-specific training, provided proper attention is paid to the concepts of motor leaning.

Ferris and colleagues are testing a similar ankle robot [9, 10], however with a few notable differences. Unlike the AnkleBOT, which uses electromechanical actuators, this device uses a pneumatic actuator to provide ankle flexion and extension torque during the gait cycle (Fig. 22.2) [11]. Pneumatic actuators are extremely lightweight, so the additional inertia felt by the subject is low compared to electromechanical actuators, particularly during the swing phase of the gait cycle. This could be extremely important in individuals who have significant weakness and poor postural control. The pneumatic actuators are mounted to a carbon fiber shell that pivots through a metal-hinged joint at the ankle. The device is capable of generating approximately 60–70% of the plantar flexor work done during normal walking [9].

The other key difference in the ankle robot being tested by Ferris and colleagues compared to the AnkleBOT is in the control strategy. As described above, the AnkleBOT utilizes a reference trajectory to establish the amount of assistance the subject receives. Ferris's device has been tested under myoelectric control (i.e., the magnitude of orthosis torque is nonlinearly related to the electromyography amplitude), foot-switch control, and push-button control. Each of these approaches puts the user in more control of the robot rather than relying on a predetermined control paradigm. Preliminary studies of these different control strategies indicate that myoelectric control was more successful in controlling the orthosis torque than using foot-switch control [12].

To date, no clinical studies have been reported on the effectiveness of using the pneumatically actuated ankle device in improving walking

Fig. 22.3 Tibion robotic system applied to the knee of a patient with left leg hemiplegia

ability and lower extremity function in individuals with neurological injuries. While most studies with this device have taken place during treadmill ambulation, it is possible to extend training to overground with proposed management of the air supply to the pneumatic actuator.

22.1.1.1 Possible Limitations with Ankle Robotic Devices

There are a number of possible limitations with incorporating ankle robots into overground gait and balance training. The first and perhaps most obvious is the weight of these devices. Strapping a 5–10 lb weight onto the distal part of the leg of a patient with significant hemiparesis may limit the users of such devices to higher functioning patients who may not benefit from such technology. While these devices are capable of providing additional limb propulsion, this assistance may be negated by the weight of the units. Another possible limitation of ankle exoskeletons is that they are tethered to either a power supply or air supply, making them impractical for long-distance walking. Finally, the size of these units strapped onto the legs of patients may force them to walk with a slightly wider gait, which may not be advantageous in the long-term recovery of stable walking patterns. Ultimately, clinical testing will be necessary to examine the influences of ankle exoskeletons in helping to restore walking ability in individuals following neurological injuries.

22.1.2 Knee Robotic Technologies

Tibion's PK100 Bionic Leg Orthosis (Fig. 22.3) is a wearable, power-assist device for the leg, which actively supplements muscle strength in order to enhance rehabilitation therapy and provide mobility assistance for patients with loss of muscle function. The system is battery-powered and supplies knee extension assistance only. Utilizing sensors throughout the device, Tibion's PK100 detects the user's actions, such as sitting/standing, overground walking, and ascending/descending stairs. Microprocessors on the device analyze this information and then apply the force needed to augment the user's actions. Patients with neuromuscular impairment due to stroke or chronic disease, such as multiple sclerosis or Parkinson disease, and patients with muscle weakness due to osteoarthritis or knee surgery may benefit from this technology. To date, no clinical studies evaluating the effectiveness of the Tibion bionic leg have been published, only case reports on the company's web site.

22.1.2.1 Potential Limitations for Knee Devices

Similar to the ankle robotic technologies described above, one of the possible limitations with the Tibion bionic knee is that the added weight of the device may negate the potential benefits of knee assistance the system can provide. That is, the system can help the patient in knee extension; however, the subject will have to provide additional hip flexion propulsion to account for the exoskeleton,

Fig. 22.4 eLEGS by Berkeley Bionics (Berkeley, CA, USA). (**a**) eLEGS is an exoskeleton actuated at the hip and knee joints while the foot is passively supported. (**b**) A patient walking in eLEGS (**a** – Courtesy of Berkeley Bionics; used with permission)

particularly in the pre-swing phase of the gait cycle. Nevertheless, clinical testing will help determine whether patients can handle the additional weight of the system while, at the same time, benefit from the added knee extension assistance.

22.2 Whole-Leg Robotic Technologies

The first generation of whole-leg exoskeletons has been restricted to treadmill-based training so that the robot can be mounted to a gantry. Devices such as the Lokomat (Hocoma AG, Volketswil, Switzerland), the Autoambulator (Motorika, Israel), LOPES [13], and Active Leg Exoskeleton (ALEX) [14] attach to the subject's legs and provide them active assistance as they ambulate on the treadmill (see Chaps. 13 and 17). The problem with restricting patients to training on a treadmill is that this mode of therapy does not allow the patient to practice real-world gait scenarios, such as walking over nonsmooth surfaces, stepping over objects, practicing standing up and sitting down, and other activities of daily living. As such, there is a tremendous need to develop exoskeletons that support overground gait training. The difficulty with translating whole-leg exoskeletons to overground gait and balance training is that these systems are quite heavy. From a control perspective, it is therefore difficult to keep them stable when patients with gait impairments try to walk with them attached to their legs. In addition, these systems require large amounts of power so that they often need to be tethered to a power supply.

A number of new whole-leg exoskeletons are attempting to overcome these limitations so that individuals with neurological injuries can practice overground walking. Jointly developed by Berkeley Bionics (Berkeley, California, USA) and the University of California under the direction of Dr. Homayoon Kazerooni, eLEGS is a wearable exoskeleton that is battery-powered and straps to the outside of the individual's legs (Fig. 22.4). The device weighs 45 lb and can be used by individuals who weigh up to 220 lb and range in height from 5′ 2″ to 6′ 4″. Both the knee and hip joints of eLEGS are actuated, allowing users to practice overground walking, standing from a sitting position, sitting from a standing position, and standing for an extended period of time. While details on the control strategy used by eLEGS are scarce, the device does not appear to utilize the impedance control strategy of its predecessor BLEEX [15]. Instead, eLEGS senses the movement intent of the patient from her/his crutches and the ground reaction forces measured by the device, then actively moves or assists the patient's legs throughout the step. Clinical testing of eLEGS is currently underway; however, no clinical or performance data has been reported on the device. It should be noted that eLEGS can be used as either a therapeutic device, in which patients can practice walking in the system, or as an assistive device, in which the device essentially moves the patient's legs through a kinematic pattern. Ultimately, the role of the system in the patient's rehabilitation program will be dictated by the return of function experienced by the patient.

Another whole-leg exoskeleton that allows individuals to practice overground walking is Rex (Rex Bionics, New Zealand) (Fig. 22.5). Similar to eLEGS, Rex is an exoskeleton that is worn by the user and can actively assist the patient in achieving a natural stepping pattern. However, unlike eLEGS, Rex is controlled using a joystick whereby the user can "drive" the system to walk over flat terrain, small slopes (up to 7.1°), and even steps. The system is battery-powered and, according to the manufacturer, can run for 3–4 h on a single charge. The system weights 84 lb and can accommodate users up to 220 lb with heights ranging from 4′8″ to 6′4″.

There are few technical details on Rex in terms of the control architecture, the degrees of freedom of the device, and the amount of assistance it can provide. In addition, there are no clinical reports discussing the usability and clinical results with the device. While it appears that the manufacturer's intent is for Rex to be utilized as a human transport system (akin to a wheelchair), it is conceivable that such a device could also be used for gait training in rehabilitation. Here, the subject could walk in Rex overground, up and down steps and slopes, and attempt to match the kinematic trajectory the system imposes. Such training may be highly effective in low-functioning patients, particularly in the early stages of injury.

Fig. 22.5 Rex exoskeleton by REX Bionics (New Zealand) (Courtesy of Rex Bionics; used with permission)

22.2.1 Potential Limitations with Whole-Leg Exoskeletons

Assuming batteries can supply sufficient power to these devices so that patients can use them for nontethered overground gait training, the most likely limitation with whole-leg exoskeletons is how effective they will be in improving walking ability in neurological patients. That is, from a motor learning point of view, the question is whether patients will adapt and improve their walking yet be dependent on the device or whether they can use these devices to reestablish independent improvements in walking ability. If patients improve their walking ability but only when in the device, the ultimate role of these whole-leg exoskeletons may be as assistive devices rather than rehabilitation devices (i.e., devices patients use for a short time to improve their own function).

The other limitation with whole-leg exoskeletons will likely be cost. These devices require precision sensors, efficient actuators, lightweight materials, and other expensive components. This may make such devices cost-preventative to most patients and only allow the largest rehabilitation hospitals to adopt them. If production volumes increase and using these systems result in improvements in walking ability, perhaps costs will come down and healthcare providers will reimburse for these systems.

22.3 External Overground Gait Training Systems

While the devices described above are focused on supplementing lower extremity force-generating capacity, an alternative approach to providing assistance to patients during overground gait and balance therapy is through the use of a body-weight support system. Here, a harness is placed around the torso of the individual being trained which is then connected to the unloading system. As the subject walks, the system can relieve them of a percentage of their body weight, making it possible for patients with excessive weakness and poor coordination to get up and start walking early after their injuries. Due to limitations in available technologies, body-weight support systems were mainly restricted to treadmill-based systems throughout the 1990s and early 2000s.

Unfortunately, recent studies indicate that training individuals with neurological injuries using body-weight-supported treadmill training may only be as good and sometimes inferior to overground gait training. For example, a multi-center randomized clinical trial compared the effects of body-weight-supported treadmill training with comparable overground gait training in individuals with incomplete spinal cord injury [16]. One hundred forty-six participants completed the protocol, which consisted of 12 weeks of either body-weight-supported treadmill training or overground gait training. It was found that there were no significant differences between the groups in terms of the lower extremity Functional Independence Measure (FIM) [17] or overground walking speed. Another study compared four modes of gait training in incomplete spinal cord injury: (1) body-weight-supported treadmill training with manual assistance, (2) treadmill training with electrical stimulation, (3) overground gait training with electrical stimulation, and (4) robotic-assisted gait training [18]. Twenty-seven subjects were trained for 12 weeks, 5 days per week. It was found that the individuals in the overground gait training group had the best outcomes in terms of improvements in overground walking speed and walking distance. Similar results have been reported for robotic-assisted treadmill training studies in subacute stroke [19].

The lingering question is why do subjects who perform overground gait and balance training improve as much as or better than those individuals who are trained on a treadmill? While there are no definitive answers to this question, there are a few plausible reasons. The first potential reason is that there are key differences between walking on a treadmill and walking overground [20]. For example, when walking on a treadmill, there is no optic flow, muscle activation levels tend to be higher, and subjects often walk at a higher cadence. Another potential reason that training overground may be more advantageous than training on a treadmill is because it allows subjects to practice functional tasks other than simply walking. As mentioned above, in order for patients to regain functional independence and participate in society, it is important that they be able to safely stand up and sit down, walk overground, navigate a step or two, and have good postural control. Unfortunately, only a small subset of these traits can be practiced on a treadmill despite them being critical components of the patient's therapy.

Fig. 22.6 ZeroG gait and balance training system (Aretech, LLC, Ashburn, Virginia, USA). (**a**) An individual with chronic stroke practicing walking in ZeroG. (**b**) A stroke patient practicing walking up and down stairs in ZeroG

There are a number of important benefits of using a body-weight support system, such as the safety it provides, the ability to get patients training early and intensely after their injuries, and the ability to progress the intensity of their training by altering the amount of weight support provided to them. Until recent years, training patients during overground gait training with partial body-weight support was not possible; however, the development of two gait training systems now supports this type of gait and balance therapy.

22.3.1 ZeroG®

The ZeroG gait and balance training system has been under development since 2005 and is now commercially available through Aretech, LLC (Ashburn, Virgina, USA). The system (shown in Fig. 22.6), which can provide up to 300 lb of static body-weight support and 150 lb of dynamic body-weight support, rides along a track mounted to the ceiling. As the patient walks, a percentage of their body weight can be removed, which helps compensate for weakness, poor balance, and other impairments common to neurological injuries. This allows patients to begin practicing a wide variety of therapeutic exercises in a safe manner. A small motor drives the trolley along the track so that, as the patient walks, the system will automatically move with them so that they only feel the vertical unloading force.

One of the unique advantages of ZeroG is that, because the system rides on an overhead track, patients can practice walking overground, up and down steps, or perform sit-to-stand or other balance tasks. As mentioned previously, these activities of daily living are important since the patients will encounter such challenges everyday in their normal lives.

The performance of ZeroG has been evaluated using both bench-top testing and human trials. Example plots of ZeroG's ability to maintain constant levels of force are shown in Fig. 22.7. In the upper two traces, a subject walked approximately 25 ft in ZeroG at their self-selected speed, turned around, and returned to their starting position. During the trial, the level of body-weight support was set to 50 lb. The error in force was approximately ±2.5 lb, mainly due to the inertia of the movement plates within the system. The lower two traces show the unloading force during a large change in vertical motion. Here, the subject was asked to drop down to one knee from a standing position two consecutive times under 30 lb of body-weight support. It can be seen that the error in force is minimal despite a change in vertical motion of approximately 16 in.

To date, there are no published clinical trials on ZeroG. Currently, there is a 3-year randomized clinical trial comparing ZeroG gait and balance training to conventional gait training in acute and subacute stroke patients [21].

22.3.2 KineAssist®

Another system capable of providing body-weight support during overground gait training is the KineAssist Gait and Balance Training System (see [22] for a detailed description of the KineAssist). The system (Fig. 22.8), which has been under development since 2002 and is now being clinically tested in various clinical sites throughout the United States, consists of a mobile base system and smart brace system. The two systems are further broken down into subsystems described below. The sophisticated control system uses Cobot technology originally developed by Peshkin and Colgate at Northwestern University for assistive devices in materials handling [23]. The Cobotic algorithms form the basis of a new class of technology that senses human movement and allows devices to follow and take direction from this movement. This adds precision and safety to lifting, guiding, and positioning. This admittance control methodology renders a haptic display that compensates for the inertial effects of the robot, allowing easy forward, up-down, and turning motions while the machine moves in response to the motion of the patient. The mobile base of the KineAssist® is powered and is highly responsive to the patient's desires for motion so that the patient does not have to pull the base. The patient's intent for motion is detected by a combination of passive joints and force sensors incorporated into the pelvic part of the patient support structure. Control algorithms move the base in response to the patient's forces and motions so that the patient's walking and turning motions are unconstrained. A software-driven "safety zone" limits the patient's vertical range of motion and implements a compliant bottom stop that gently catches the patients when they lose balance.

In addition to simply acting as a fall-arresting device, this device can partially support the patient's weight at the level of the pelvis, and the system is also capable of comfortably applying forces to the body. The KineAssist® is able to produce unweighting of the patient (partial body-weight support training) up to 150 lb of vertical force. The vertical column is powered to provide this force continuously and at the same time to easily allow the vertical motions of the pelvis and torso, which are a part of normal gait. The unweighting feature is rated to 150 lb, but the KineAssist® is designed for patients up to 350 lb, and it can safely bring such a patient to a stop after only a few inches of fall. (The clinician selects the threshold distance for identifying and stopping a fall.) The therapist has the freedom to change parameters and assist or challenge the patient to the level that is necessary to gain the best clinical outcomes.

22.3.3 Limitations with Overground Body-Weight Support Systems

The potential limitations with the devices described above are device specific. For example, with ZeroG, patients are restricted to walk under the track and cannot deviate more than a couple of feet without feeling a large horizontal restoring force. With the KineAssist, the responsiveness of the system is necessarily slow for stability purposes so that the patient can feel the weight and inertia of

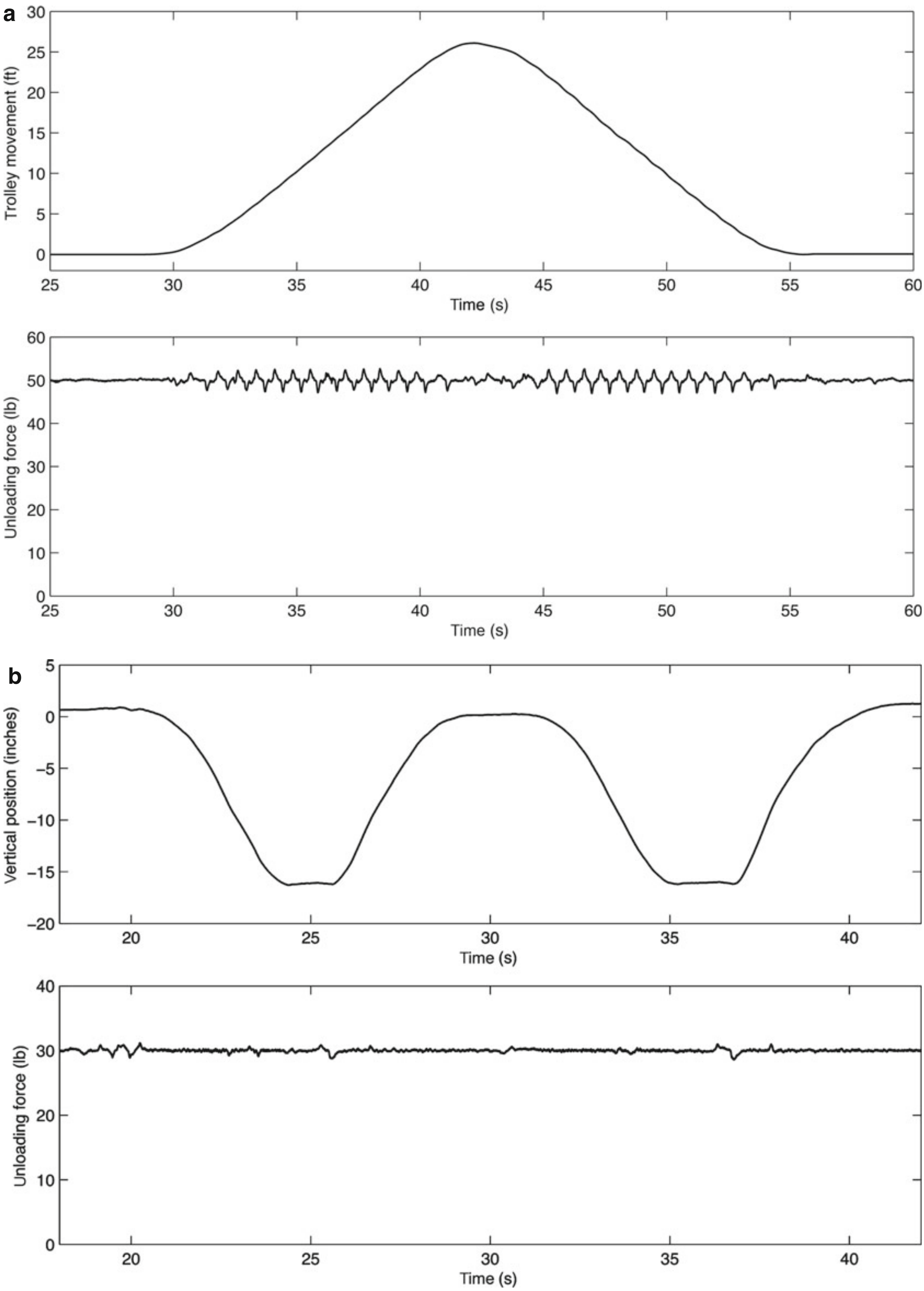

Fig. 22.7 ZeroG performance during an overground walking trial (**a**) and a balance task (**b**)

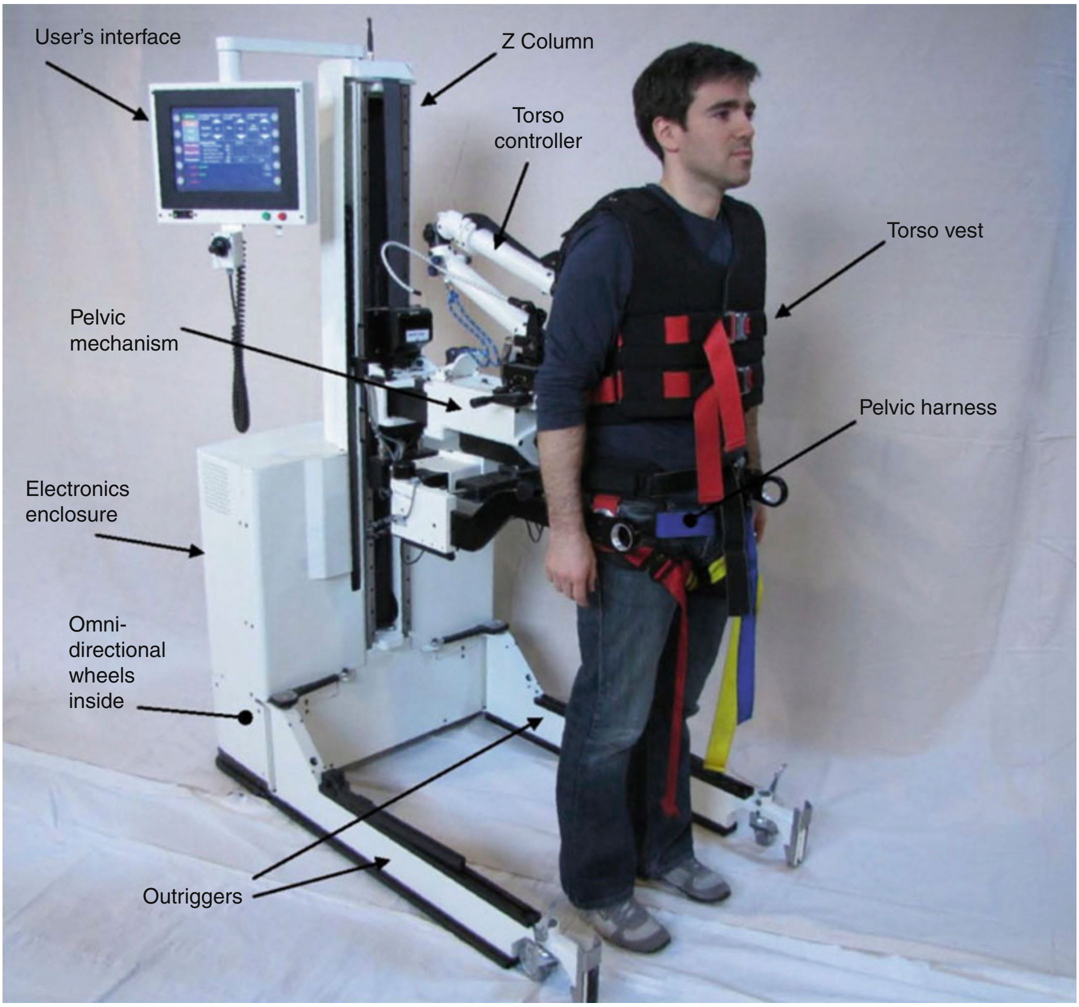

Fig. 22.8 KineAssist gait and balance training system (Courtesy of Kinea Design, LLC, Evanston, IL; used with permission)

the device as they walk, stand up, and perform other gait and balance activities. In addition, because KineAssist rolls on casters, patients are restricted to overground gait and balance training on smooth, flat surfaces.

Similar to whole-leg exoskeletons, another major disadvantage of these devices is cost. Because these systems contain numerous actuators, precisions sensors, and other custom components, the pricing for these systems only allow the largest rehabilitation centers to adopt the technology. Perhaps with increases in production volume, the costs will come down so that smaller outpatient clinics can also adopt these devices.

22.3.4 Future Directions

The field of rehabilitation robotic technology is at the very early stages, particularly as it relates to robots that promote overground gait training. In order for these devices to truly be integrated into the clinical setting, a number of factors will need to be explored and tested.

- Patient safety: The use of robotic technology that involves forces to control motion is inherently dangerous and unstable when interacting with patients who show a wide variety of movement variations. Safety standards need to be developed to assure that the robotic application does not overstress the musculoskeletal system or induce high forces that cause tissue trauma.

- Optimized parameterization of exercise components: The success of any robotic technology will be limited by the effectiveness of the exercise regime with which it is used. As such, clinicians and scientists must be careful to avoid generalizing the effectiveness of a particular robotic technology within a particular patient care setting unless that application has been well tested and the effectiveness validated in a suitable, well-controlled clinical trial. The parameters for the exercise sessions that are designed for an exercise intervention must be scalable for each patient case, and future technologies will need to allow clinicians access to the controls of the devices so that they can alter these parameters appropriately.
- Clinical feasibility: Issues such as cost, weight, size, and flexibility of function will ultimately determine the clinical feasibility of any robotic system within a clinical or home-exercise environment. Future directions in robotic technology will need to take into account the patient's comfort, the ease of donning and doffing, and the tolerance for interacting with new technology during the design process.
- Problems with overground travel: A device that will accompany any patient as they move overground will need to assure safety in the case of loss of balance and falls, as well as collisions with objects and people, and moving through different flooring environments and negotiating around furniture. Future devices will need to occupy small spaces and catch and maintain the person's full body weight after a fall.

As the field moves forward, each of these factors needs to be strongly considered as new robotic technologies are developed and existing technologies refined.

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