# Body Weight Support Devices for Overground Gait and Balance Training

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# 33 Body Weight Support Devices for Overground Gait and Balance Training

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**Abstract**

Regaining the ability to walk overground, to climb stairs and to perform other functional tasks such as standing up and sitting down are important rehabilitation goals following neurological injury or disease. However, these activities are often difficult to practice safely for patients with severe impairments due to the risk of injury, not only to the patient but also to therapists. The emergence of various technologies that provide a degree of body weight support can play a role in rehabilitation focused on recovering overground gait and balance functions. These can greatly reduce the risk of falls and thus allow more intense and longer training sessions. Therefore, the systems empower individuals with the ability to practice the types of activities and functions they need in order to return home and to be reintegrated into the community as much as possible. This chapter explores the origin of body weight supported devices and considers which groups could derive benefit from the training. An overview of the main training platforms available today—which comprise both robotic and non-robotic technologies—is then provided, followed by a discussion regarding outcomes of the devices thus far and possible future directions of the technology.

**Keywords**

Robotics · Rehabilitation · Body weight support · Gait · Walking · Stroke · Spinal cord injury

## 33.1 Clinical Rationale for Body Weight Supported Training

### 33.1.1 Origins and Evolution

In body weight supported (BWS) gait training, a harness is placed around a person's torso and / or pelvis and connected to an unloading system in order to provide a variable degree of unloading as the subject walks. Originally motivated by a rich literature of studies with felines [6] and rodents [18] which demonstrated that stepping patterns could be restored through treadmill-based

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training with BWS, this training method enables patients with a high degree of weakness and/or poor coordination to undergo gait training following neurological and musculoskeletal injuries.

One major advantage of body weight support devices is that they reduce the fear of falling and thereby allow individuals to concentrate more freely on the main training tasks. It has been shown that fear itself can have effects on gait characteristics; for example, older adults who reported being more fearful during walking tended to walk more slowly with a greater step width and shorter step length in one study [14].

There are low-cost solutions available for providing assistance from therapists during transfers and gait training such as the gait and walking belt devices [46], which allow therapists to apply supportive forces close to a patient's centre of gravity and provide handles for assistance. It has been shown that the risk of falling was lower in rehabilitation programs incorporating gait belts and similar devices, and that using a gait belt during assisted falling reduced the risk of injury [50]. However, due to the exertion levels required and sometimes awkward postures required for performing assistance, manual gait training has been associated with increased risk of injury to therapists [12].

Moreover, research has shown that increased fall efficacy—a term representing an individual's degree of confidence in conducting activities of daily living without falling—is a predictor of gait and indeed other functional rehabilitation outcomes [8]. Fear of falling may have contributed to the findings of some earlier research, for instance with incomplete spinal cord injured subjects [17], which pointed to greater gains being achieved through treadmill-based as opposed to overground walking, since in the latter studies, the subjects were supported only by simple ambulatory assistive devices such as crutches and canes and hence likely had a more pronounced fear of falling during the training.

Another possible contributor may be that walking with body weight support could reduce fatigue and hence increase the feasible training duration. Indeed, it has previously been shown that body weight support reduces the net metabolic rate during gait [16]. Furthermore, 'verticalisation' of individuals, which can be promoted through BWS, is an important goal in rehabilitation of different groups such as stroke patients, since it can have benefits regarding circulation, prevention of pneumonia and clots, while also providing stimulation for the autonomic and sensory nervous systems [26].

The first generation of body weight support systems were mounted over a treadmill with therapists providing assistance to the patient. The observation that the training duration and consistency were frequently limited by therapist fatigue led to the development of robot-assisted gait training platforms such as the Lokomat [11]. Beneficial effects on kinematic, kinetic and spatiotemporal parameters of robot-assisted training have been noted, for instance, for chronic stroke patients [7].

However, other studies have suggested that for certain groups such as subacute stroke participants with moderate to severe walking impairments, the variability and diversity afforded by overground walking may be more beneficial than treadmill-based training with robotic assistance [19]. This could be partly due to the many changes in gait biomechanics that occur when walking on a treadmill [30]. It has also been argued that the treadmill belt could make the training less intense and challenging, and that the treadmill-based systems cannot provide task-specific overground training [25].

Several new body weight support systems now offer a safe environment that is not dependent on treadmills, which help individuals to overcome their fear of falling and thereby to practice overground gait. This technology could lead to improved rehabilitation outcomes compared with previous treadmill-centred methods. Researchers have argued that overground training could prove beneficial due to greater kinematic variability being permitted in addition to offering gait training in a more real-world environment [56].

### 33.1.2 Target Groups

There are various groups of people who can benefit from body weight supported gait and balance training such as individuals who have suffered from an injury or neurological pathology. Though the various patient groups are affected in different ways and have different patterns of gait and balance impairment, the main task of the training devices remains the same: to provide a degree of body weight support so that the people can perform gait and balance training with a reduced risk of falling.

The incidence of spinal cord injury (SCI) has been estimated to lie between 10.4 and 83 per million people per year [57]. In addition to the detrimental effects on sensory and motor function, which can manifest in gait as reductions in gait speed and alterations in walking pattern [28], SCI can lead to secondary health conditions such as ulcers, amputations and major depressive disorder [27]. In addition to potential benefits with regard to ambulation, robot-based rehabilitation has shown positive results concerning posture, intestinal, cardio-respiratory and metabolic function [20].

Over 50 million people per year worldwide have a traumatic brain injury (TBI) [32], which is characterised as a change in brain function and other pathology due to an external force [36]. As well as the impacts on cognitive, behavioral, and emotional functioning, the effects on motor skills can lead to considerable alterations in gait, including decreased walking speed and step length, with exaggerated knee flexion on initial ground contact with the foot being evident [54]. The impact on walking also leads to increased incidence of falls in this group [35]. Independent walking is a common discharge rehabilitation goal for TBI patients [24].

Stroke is the second leading cause of death globally and a major cause of long-term disability in adults [45]. Furthermore, as stroke is associated with increased age, the prevalence of stroke could well be increasing due to the ageing of the population [15]. It can lead to impaired ambulatory function, which is in turn associated with a decreased quality of life [39].

Multiple sclerosis (MS) is a disease that causes the myelin sheath of nerve cells in both the brain and spinal cord to be damaged, leading to sensory and motor impairment and physical and mental issues. The incidence of multiple sclerosis is over 35 per 100,000 people and appears to be increasing with time [52]. MS manifests in gait by decreased gait speed, endurance, step length, cadence and joint kinematics [9]. For multiple sclerosis patients, in common with the other patient groups, gait is strongly associated with wider participation in society [23].

Cerebral palsy (CP) represents the most prevalent physical disability in children, affecting from 2 to 2.5 per 1,000 children in the United States [29]. CP can affect gait development in various ways, and CP patients typically have stiff knee action in the swing phase, crouched gait, excessive hip flexion, intoeing, and ankle equinus (limited dorsiflexion of the foot due to a lack of flexibility in the ankle joint) [55]. As noted for the other groups in this section, lower limb and gait dysfunction can have wider impacts on the overall quality of life for CP patients [22].

## 33.2 Overground Training Devices

### 33.2.1 Robotic Devices

**Motivation** Robotic body weight support devices use actuation to control the forces acting on an individual, possibly in multiple directions and varying over the gait cycle. They can actively track the movement of a subject in both the vertical and horizontal directions during gait, thus avoiding undesired interference between the individual and the device itself.

Adjusting the level of unloading is usually conveniently done through user interfaces that are operated by therapists. Moreover, the devices, which are summarised in the following sections, can be broadly categorised as being ceiling-mounted or mobile frames.

**Ceiling-Mounted Systems** The ZeroG® gait and balance training system (Fig. 33.1a) is commercially available through Aretech, LLC (Ashburn, Virginia, US). The system can provide around 200 kg and 90 kg of static and dynamic of body-weight support, respectively. Mounted to an overhead track, a small motor propels a trolley to track a patient's movements. More than one ZeroG trolley can be placed on the same track, thereby providing the opportunity for multiple patients to train simultaneously. Patients can practice walking overground, walk up and down steps, perform sit-to-stand movements and practise other balance-centred tasks. These activities are important since the patients will encounter such challenges in their everyday lives.

The SafeGait 360° (Gorbel Medical, Victor, NY, U.S.) and the Vector Gait & Safety System® (Bioness Inc., Valencia, CA, U.S.) are further examples of ceiling-mounted body weight support systems that actively track a subject's movement during gait in the longitudinal direction.

A drawback of systems based on single rails is that they restrict the user to a specific path. Another limitation is that the cable will unavoidably transmit lateral force components whenever the individual moves laterally. Even if these lateral movements are small during gait, the 'pendulum effect' due to the mounting below a pivot could potentially disturb balance or support it more than intended or needed [13, 41]. This stabilising effect makes it more difficult to purposefully train lateral balance. However, there can be benefits from stabilising a patient in the lateral plane in some cases, particularly those with lateral propulsion syndrome [38].

Therefore, multiple systems have been proposed that enable training in a 3D workspace. The Free Levitation for Overground Active Training (FLOAT) system, commercially available through Reha-Stim (Schlieren, Switzerland) and shown in Fig. 33.1b), is a 3D body weight support system that capitalises on cable robot technology developed at ETH Zürich [48]. The system transmits forces to a person via wires that are actuated by motorised winches positioned at the ceiling in the four corners of the desired workspace.

Conventional cable robots tend to have a limited workspace because the angle of the cables with respect to the horizontal plane determines how much force needs to be transmitted for a given vertical unloading level. To enable a large workspace without incurring excessive cable forces, the FLOAT uses a mechanical configuration of moving cable deflection units (pulleys) [51]. The deflection units are not actuated but rather are moved by the tension in the cables they deflect. The design reduces moving masses to a minimum and it enables control of a three-dimensional (3D) force vector, including relieving patients of a percentage of their body weight and providing longitudinal assistance or resistance.

Nevertheless, a design drawback of the FLOAT is that, as in conventional cable robots, all the winches must act in combination to actuate the different degrees of freedom, rather than in a decoupled fashion. This requires high-power actuators because they need to serve both the low-speed, high-force vertical degree of freedom and the high-speed, low-force horizontal degrees of freedom.

The RYSEN™ (Motek Medical B.V., Houten, the Netherlands) is also a cable robot but has lower-power motors. This 3D body weight support system (Fig. 33.1c) mechanically decouples the degrees of freedom across the motors such that these can make different speed-torque trade-offs [42]. The RYSEN uses moving cable deflection units on rails and posterior-anterior motion is actuated by motors. Springs are applied in series with two main motors being used for predominantly vertical actuation and a double-sided variable-radius winch for lateral actuation. The low-power motors limit the bandwidth of closed-loop control in the vertical direction but the design does achieve very good force tracking in the horizontal direction [42, 43].

Besides cable robot technology, another option to provide 3D body weight support is to use gantry systems. The Active Response Gravity Offload System (ARGOS) is used by NASA for astronaut training in simulated reduced gravity environments and is based on an active overhead gantry crane system. Motion in the horizontal plane is controlled by electric motors, while the degree of body weight support is controlled by a crane connected to the user via a steel cable and shock absorber.

The NaviGAITor is a similar example of a multidirectional body weight support system [44]. A movable bridge is mounted on a pair of rails to enable movement in the longitudinal direction, while lateral motion is permitted by movement

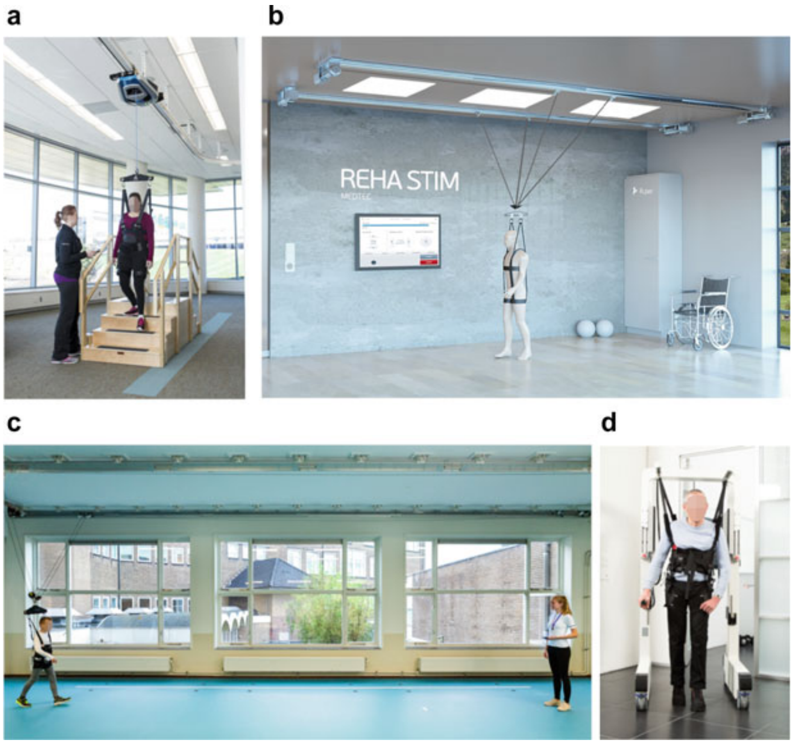


**Fig. 33.1** Robotic body-weight support devices. **a** Zero-G (courtesy of Aretech, US), **b** THE FLOAT (courtesy of REHA-STIM MEDTEC AG, CH), **c** Motek Medical's RYSEN$^{TM}$ at the Rehabilitation Center Heliomare, Wijk aan Zee, NL (courtesy of Motek Medical), **d** ANDAGO (courtesy of Hocoma AG, CH)

of a trolley along the bridge. Actuation is realised in these two directions via electric motors, and a further motor drives a hoist to provide vertical forces in order to realise different degrees of body weight support.

A major advantage of 3D systems over systems based on single rails is that, in principle, they do not restrict the user to a specific path, and, if they are sufficiently transparent, do not cause restoring horizontal forces, thereby preventing the aforementioned pendulum effect. However, a 3D setup may impose different limitations on the practice space; for example, it fits less easily into narrow or curved rooms or corridors. Furthermore, such a device can typically only support one patient at at time, the practice walking length is limited, and the design may require high ceilings for installation.

An inherent limitation of the gantry-based systems is that large masses need to be moved when tracking a walking user. Even if closed-loop force control is applied, the user will feel some remaining inertia because the reduction in apparent inertia is limited in causal control schemes [10]. This limits the devices' ability to render purely vertical forces on a user, potentially disturbing their gait by imposing undesired horizontal force components.

**Mobile Frames** The Andago® (Fig. 33.1d), developed by Hocoma AG (Volketswil Switzerland), comprises a mobile frame mounted on wheels and a BWS [34]. Patient trunk movements are tracked, and hence he or she can practice walking without being confined to one specific training room. The training platform can be used in patient-following mode in which the person's movements are followed not only in the forward and backward directions but also in turning movements, straight-line mode in which turning inputs are not followed, and finally in manual mode in which the device is controlled by a therapist via a joystick.

A further system which was originally mobile is the KineAssist [40], which interacts with users through a pelvis and torso harness. The device senses interaction forces at the pelvis and thereby controls the movement of a robotic platform. Today, however, the KineAssist is only available as a treadmill-mounted system from Woodway (Waukesha, WI, U.S.).

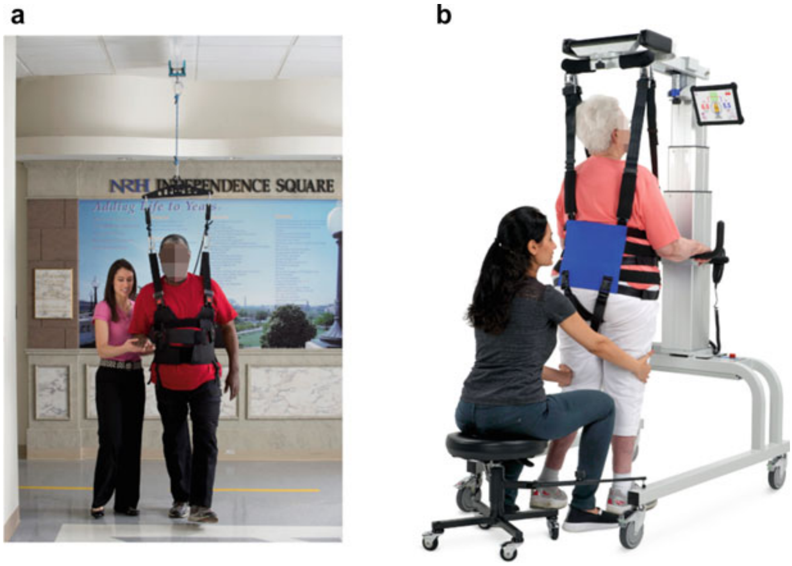


**Fig. 33.2** Passive body weight support devices. **a** Zero-G passive (Courtesy of Aretech, US), **b** LiteGait (courtesy of Mobility Research, US)

### 33.2.2 Non-Robotic Devices

**Motivation** Various non-robotic systems are available on the market that provide static body weight support during overground gait and balance training. The principal advantage of these systems is clearly their cost: they do not require the expensive sensing and actuation hardware of their robotic counterparts. The disadvantage is that the vertical support cannot be precisely controlled and the options for applying forces in the horizontal plane—for instance perturbation forces for balance training—are more limited. Nevertheless, the devices do allow people who cannot support their entire body weight to practice overground walking.

**Ceiling-Mounted Systems** A large number of commercial solutions are available that are based on passive trolleys mounted on rails in order to provide support during overground ambulation. For example, the design of the ZeroG-Passive system (Aretech, LLC, Ashburn, VA, US) closely follows the robotic ZeroG platform, but rather than actuating the trolley position via a motor, it is simply pulled along by the patients as they ambulate (Fig. 33.2a). The FreeStep SAS (Biodex, Inc, Shirley, New York, US) operates similarly to the ZeroG-Passive and also uses small and lightweight trolleys.

In light of the findings concerning how BWS reduces the risk and fear of falling, a particularly innovative building design is the Shirley Ryan AbilityLab in Chicago (formerly known as the Rehabilitation Institute of Chicago, RIC). Many areas of this hospital are equipped with rails mounted to the ceiling such that training with a safety harness and passive trolleys is not limited to dedicated gym areas. Instead, users can walk with a safety harness along ‘patient highways’ in many locations in and close by their own rooms. This reduces the risk of falls and reduces the transfer time between therapy sessions. If these aspects are considered when planning the construction of a hospital or rehabilitation center, the installation of such rails is much less expensive than retrofitting. However, the noise levels of passive carts on the rails should also be taken into consideration.

**Mobile Frames** The LiteGait system by Mobility Research (Tempe, AZ, U.S.) comprises a mobile cart mounted on castors and an overhead bracket for attachment to a harness (Fig. 33.2b). Owing to a locking system, the device can be used for either treadmill or overground training.

Other castor-mounted systems include the NxStep$^{TM}$ Unweighing system by Biodex (Shirley, New York, US) and the PhysioGait

(HealthCare International, Langley, US). Like their mobile robotic support counterparts, mobile frames are not tied to being used in a specific training room. However, a disadvantage is the relatively large mass of the device that must be moved by the patient, which potentially affects the gait biomechanics.

## 33.3 Device Characteristics

### 33.3.1 Transparency

To maximise motor learning outcomes and functional gains, training devices should only provide just enough support to create a safe environment; the devices should be able to 'hide' their presence in terms of interaction forces between the device itself and the user. The degree to which this is possible is often referred to as transparency [5]. This can be promoted through hardware design that emphasises low inertia and friction as these factors can lead to higher interaction forces and distort the mechanics of gait.

In robotic body weight support devices, the ability of a system to track the movement of an individual will govern the realisable degree of transparency to a large extent. As mentioned in Sect. 33.2.1, even with closed-loop force control, the device dynamics cannot be 'hidden' completely, and the physical mass of a device is a governing factor of transparency, with friction between static and moving parts also playing a role. Again, systems mounted on mobile platforms and 3D gantry-based systems tend to have limited transparency since relatively large masses must be moved by the user.

### 33.3.2 Vertical Support Forces

For body weight support systems, levels of body weight support above 30% appear to significantly alter some gait characteristics such as the kinematics and kinetics of the hip and knee joints [3]. Indeed, modelling has shown that there could be changes in the sign of joint moments above this level of unloading [43]. Therefore, an excessive level of body weight unloading potentially causes large kinematic and kinetic changes from physiological gait and therapists should aim to apply levels of vertical support below this apparent threshold during training sessions.

Besides the mean value of support over the gait cycle, variations in vertical unloading should also be considered. Some systems intrinsically exhibit variable forces, especially when using counterweights or springs. A prevalent paradigm is to keep vertical unloading forces as constant as possible, with the argument in favour of this approach being that gravity itself is constant. This presumed requirement increases device complexity to keep force levels constant despite the oscillatory vertical movement of the user during gait. This goal is often pursued by closed-loop force-controlled actuation. However, although a constant unloading vertical force can relieve the body of a portion of its weight, its inertia in the vertical direction remains unchanged, which disturbs the relationship between gravitational and inertial forces and may thus alter the natural frequency of gait.

In fact, simulation results suggest that a simple passive spring suspension—in which a spring stiffness is chosen to favour natural gait cadence—distorts gait mechanics to a lesser extent than more complex approaches that actively control the vertical force to a constant level [4]. During gait, acceleration-dependent inertial forces can largely be compensated by position-dependent spring forces and the relationship between weight and inertia is thereby maintained constant despite the unloading, and therefore, the gait frequency remains closer to its physiological value (withoutunloading). Hence, a passive elastic suspension is not only easier and less expensive to realise, but also may disturb gait to a lesser degree than an actively controlled constant force suspension.

This insight can, furthermore, influence the design of robotic systems, namely the inclusion of series-elastic elements in combination with low-bandwidth actuators. For example, the RYSEN employs series springs that cover oscillations in the vertical direction during gait where the low-power motors lack bandwidth. Only for movements with lower frequency need the motors move to change the setpoint of the springs (mainly in order to manoeuvre over stairs or to sit down).

### 33.3.3 Longitudinal Forces

The notion that individuals would prefer zero or positive forces in the longitudinal direction (forces acting in the forward direction of ambulation) due to energy efficiency considerations has been challenged by research using the RYSEN [43]. Though resistive longitudinal forces applied by the devices would require greater energy consumption by the subject during gait, healthy subjects in this study tended to favour small negative forces when walking in the robotic platform. The reason suggested was that unlike a backward fall, a forward fall can be recovered through a swift movement of the swing leg and, therefore, a small negative force encouraging a slight forward lean during gait could allow subjects to feel safer and have less fear of dangerous falls.

Overground gait training devices can also include perturbation forces in various directions, including along the longitudinal axis. For example, an additional module has been integrated into the FLOAT platform to apply perturbation forces in different directions [37]. It has been argued that applying perturbations in this way, as opposed to a treadmill, presents less risk of falling and hence less risk of injury and a reduced sense of fear during the training.

### 33.3.4 Lateral Forces

As mentioned in Sect. 33.2.1, research has pointed to a pendulum effect from the body weight support mechanism itself: the systems can produce lateral restoring forces which decrease the challenge of maintaining balance in the frontal plane. Therefore, systems that reduce these restoring forces could be useful for gait training that incorporates active balance control. Systems that do not permit lateral movement are likely to lead to greater restoring forces and hence may limit the ability to train balance in the frontal plane, which is an important element of gait [33].

However, systems that, in principle, do allow lateral movement may still generate undesired lateral forces, depending on their degree of transparency. Moreover, the point of application of the resultant unloading force needs to be considered to know which stabilising or destabilising moments are applied about the center of mass as discussed in the next section.

### 33.3.5 Harness and Attachment

Ease of attachment to the harness is important as long set-up times will detract from the time available for actual training. Wheeled mobile platforms should offer sufficient space so as to allow wheelchair access and to avoid necessitating additional transfers. Comfort while exercising in the harness should also be considered in the design as discomfort may limit the training duration tolerable by the subjects and, similarly to the fear of falling, may detract from their concentration on the active gait task. This has been considered in some designs for which different harness versions are available for male and female users.

The attachment of the harness also determines the line of action of the resultant force acting on the user and how the unloading forces are distributed along the body. The location of the line of action with respect to the body's center of mass defines the resultant moments of the unloading force. Inmoments caused by ground reaction forces, this governs the rate of change of centroidal angular momentum, which is a key variable for bipedal stability and balance control.

Results with able-bodied subjects indeed indicate that the self-selected walking speed is affected by the attachment mechanism [43]. Furthermore, the optimal type of attachment may vary according to the degree of impairment of the subject. For less impaired subjects, attachment near the pelvis could be better since this will not produce stabilising moments about the hip joint, while for individuals who are less able to maintain their balance independently, attachment higher up on the torso would be better due to the stabilising moments this affords.

For treadmill walking, attachment via a harness has been shown to reduce vertical acceleration. This is due to restrictions in both linear and rotational movements imposed by the harness that lead to the trunk being less able to absorb shocks than in normal gait [1].

## 33.4 Outcomes of Overground Gait Training

There have been a limited number of studies thus far which have investigated the outcomes of applying the various devices described here to overground gait and balance for different patient groups. In contrast, there has been a greater volume of research focused on the outcomes of treadmill-based training and rehabilitation as summarised, for instance, in the review by Wessels et al. [53]. Although research has suggested that conventional therapy incorporating overground walking with manual assistance seems to yield broadly comparable outcomes as compared to treadmill training with BWS [31], there have not been comprehensive comparisons between overground training using BWS and treadmill-centred training. Nevertheless, the results from studies using BWS devices in rehabilitation have generally been encouraging so far; some of the main findings from the studies with overground devices are summarised below.

Huber and Sawaki compared overground gait training for non-traumatic SCI using the Zero-G system, finding better outcomes in terms of sphincter control for the robot-assigned group compared to standard-of-care therapy [21]. Both groups achieved significant gains in Functional Independence Measure (FIM) scores but no significant cross-group differences were apparent.

Anggelis et al. compared the outcomes of training with and without dynamic body weight support using the Zero-G platform in traumatic brain injury patients [2]. The Zero-G group demonstrated significantly greater improvements in functional independence measures (FIM) as well as cognitive improvements than the control group. The authors suggest that this is due to the greater intensity facilitated by dynamic body weight support systems. Furthermore, the importance of reducing the fear of falling and thereby allowing the individuals to concentrate more fully on the training tasks was highlighted.

Brunelli et al. conducted a study with subacute stroke patients and compared body weight supported overground training with the LiteGait to conventional physiotherapy [8]. While both groups showed improvements in all the outcome measures—which included the Rivermead Mobility Index, Barthel Index, and the Six Minute Walk Test—greater gains were shown concerning the Functional Ambulation Classification for the individuals who participated in the BWS training.

Tay et al. compared outcomes for patients undergoing training with the Andago system in addition to conventional therapy to other individuals who only had conventional therapy [47]. Statistically significant FIM gains were made in both groups; though the robotic training group showed greater improvement in functional ambulation scores, there were no statistically significant differences in the other outcomes.

Van Hedel et al. assessed the use of the Andago platform for children and youths with gait impairments [49]. They observed that the device prevented several falls and also that variability in stride duration and the degree of inter-joint coordination were higher with the overground training than treadmill walking.

## 33.5 Future Directions

The cost of the various overground robotic devices remains an obstacle to their widespread adoption in rehabilitation programs. Notably, the actuators used to track gait movement lead to additional safety requirements and hence higher certification costs. Non-robotic systems are, therefore, much less expensive than robotic body weight support platforms. Since the former category may provide most of the potential benefits of the body weight support systems at much lower cost, research comparing usability and clinical outcomes—for example in terms of functional gait—between passive and robotic systems is needed in order to evaluate whether the additional costs of actuation are actually justified.

More generally, there remains a paucity of results concerning clinical outcomes from using the various devices for different patient groups. Additional evidence for the efficacy of the devices from studies with larger subject groups is needed to justify funding of the devices by health care systems. Though there are promising results showing improvements achieved through overground robotic training, whether these lead to improved ambulation in the long term remains uncertain. Therefore, studies including longer-term follow-ups for the various different types of training are needed, along with investigations as to whether or not training in the clinical setting can really translate into increased community participation and integration.

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