Review and Classification of Human Gait Training and Rehabilitation Devices

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Abstract.

The number of people with reduced mobility capabilities increases every year. This reduction arises mainly due to spinal cord injuries; strokes which caused hemiparesis; or due to an advanced age. This decrease in mobility is a factor that influences both their quality of life and their dependence of others in daily life.

Thus, it becomes necessary to find means and tools to prevent, compensate, improve or help to restore and increase the mobility of the affected people. The main expectation is that such means help to recover or ameliorate their independence in their daily life. Traditional training employs a treadmill with a support-weight system. This training is based on the principle of repetition of all the physical movements of a gait and has shown to produce good results in terms of rehabilitation of patients. However, this therapy requires two or more therapists in assisting patients during walking, to hold and adjust the patient's lower limbs to correctly produce the desired gait. Thus, it requires a substantial commitment and effort of the therapists [1], and it is very expensive in terms of human resources. This leads to a boost on the population healthcare and assistive services demand and, thus an increase in the need for care givers.

Assistive mobility robotic devices for gait training of disabled patients in treadmills and in the ground are one successful alternative. Other alternatives include devices that allow a broader training of patients, in different ground types, and the repetition of gait movements in uphill, downhill and trip.

This paper reviews state of the art training gait devices focusing on passive and active devices. Passive devices rely on the principle of Gravity-Balancing in that they try to reduce or eliminate the effects of gravity during walking. Active devices are usually classified according to three different approaches: (i) treadmill-exoskeleton based devices, (ii) robotic manipulators generating different types of gait patterns, and (iii) mobilite devices. In this review, several examples of current devices are presented.

Keywords. Locomotion, gait rehabilitation, orthosis, robotics

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Introduction

The application of robotics for rehabilitation, implies on the use of robots for gait training of disabled patients in treadmills and in the ground. This purpose tries to replace or complement the therapists' work so that each patient can receive enough therapy and, therefore, achieve an optimal recovery. It also tries to actively involve patients onto the training, since motivation is crucial to facilitate and ameliorate motor learning [2]. Intensive research in robotic gait trainers led to robots capable of providing the necessary assistance to therapists.

Robotic gait trainers can be passive or active. In a passive device, the patient member has to provide for the required strength for the lower limb movement. These devices just have springs and links. On the other hand, active devices have to bring the required energy to allow the lower limbs movements, and usually employ actuators or motors [3].

This paper reviews state of the art training gait devices, both passive and active.

1. Passive Devices

Usually, a passive device shows up the following characteristics: it is passive, so it is composed of links and springs; it is safe; and has a simple patient-machine interface that accommodates a number of variations in geometry and inertia of the patients [4]. Figure 1 shows a schematic of the basic components of this mechanism and the prototype developed in [4]

Works addressing balance constraints employing these devices have focused on the effects of the rehabilitation machinery in the stability of posture during walking, and in determining the nature of internal forces and moments of members [4,3]. The principle behind this device is based on a hybrid method: the center of mass of the patient's leg is found using a parallelogram mechanism, and springs are placed in suitable positions for them to balance the effect of gravity throughout the movement of the legs. These concepts are described in detail in [4].

Safety is a determining factor in choosing a passive device. Normally, patients feel more comfortable and safer to wear a passive device then an active device. Further, it is adjustable to the geometry and inertia of each individual so that it achieves the desired and needed level of balance. The device can also apply adjustable forces to help swing the member and in the forward propulsion during walking. Thus, the assistance to the movement becomes increasingly smaller as the patient progresses in his rehabilitation [4].

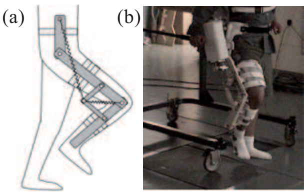

Figure 1. (a) Basic components of a gravity-balancing mechanism [4]. (b) Subject wearing a Gravity-Balancing device [4].

2. Active Devices

Active devices are usually classified according to three different approaches.

One approach is based on treadmill training in which a support holds the patient thus reducing his weight. In practice the patient is wearing a robotic device that helps to generate a gait pattern at ground level. In another approach a robotic manipulator holds the patient's feet and generates / simulates different types of terrain and human gait patterns, e.g., a flat walk, climbing stairs and trip. In this approach, the patient is also sustained, which reduces his weight. Finally, there are mobile devices that the patient wears and allows him to move on the ground without any help from others.

In the following a more detailed description of each of these approaches is presented.

2.1. Treadmill Training Devices

The most prominent method for walking rehabilitation is the treadmill training with body weight support. A gait pattern can be automatically activated by using a treadmill with a weight-support system, given that it is indispensable the foot contact with the ground to trigger a gait reflex. This technique is inspired on the neural control of vertebrate locomotion [5]. Preliminary experiments with brainless cats have successfully conducted the training of its gait on the treadmill. Based on these observations a large number of research teams began to carry out similar experiments with humans on treadmills.

Traditionally, patients with locomotor disabilities use a frame that supports their body weight over a treadmill. Two or three therapists then manually assist the movement of their legs throughout the lower limbs movement on the treadmill, and stabilize the patient's posture. However, this training requires a lot of effort from the therapists, and robotic devices have started to be developed by several research groups to assist the patient on the treadmill.

One of these robotic devices is the Lokomat® , by Hocoma [6]. This device consists of two robotic orthoses with two degrees of freedom for each and a holder that supports the pelvic girdle. Each orthoses controls knee and hip joints (Figure 2) a. It is adjustable to the length of the upper and lower segments of the leg, and to the extent of the patient's hip. DC motors carry out the joints' actuation and the angles are measured by potentiometers. The reference trajectories used to control the movement are physiological angle trajectories of hip and knee. In order to provide for planar lateral stabilization, the Lokomat® structure is attached to the treadmill through a four-bar mechanism. The patient's legs are connected to the device by three adjustable Velcro straps per leg, as shown in Figure 2 a.

Usually, users of the device perform a fixed gait pattern that is obtained by controlling angular position of the joints' trajectories. However, it is important to ensure that the patient actively walks, instead of having his legs passively moved by the Lokomat® [7]. This requirement idea led to the development of an algorithm to adapt the gait pattern, which enables to walk actively in the system, with some degree of voluntary locomotion, with a variable gait pattern.

A similar system to the Lokomat is LokoHelp [8], depicted in Figure 2 b. This is an electromechanical device placed in the middle of the treadmill, parallel to the gait's direction and fixed at the treadmill front by a simple hook. An additional mechanism supports the weight of the patient, stabilizes and positions the system above the treadmill.

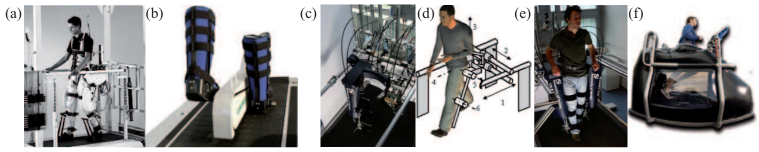

Figure 2. (a) Lokomat, (b) LokoHelp, (c) degree of freedom that actuates on the pelvis and (d) schematic of degrees of freedom in LOPES. (e) Subject wearing LOPES. (f) G-Trainer^{TM}

During therapy, the LokoHelp guides the patient's legs according to a defined walking pattern. There is no slippage since LokoHelp is indirectly driven by the surface of the treadmill. This device ensures a continuous, rhythmic motion throughout the treatment. As the LokoHelp allows training of the control of posture, knee extension, active impact of the foot's sole and active hip extension.

Another project that uses the treadmill is LOPES of University of Twente (Netherlands) [6]. This is an exoskeleton type of robot and allows the execution of forces or moments onto the patients' legs. The robot moves in parallel with the patient's legs such that all the patients' movements are still possible. Because robot joints correspond to human joints, it is easy to impose limits on the security forces and moments applied.

The exoskeleton is physically attached to a support located at the height of the pelvis (Figure 2) [3] c. The system has eight degrees of freedom (Figure 2 d): two for the horizontal translation of the pelvis and three rotational joints per leg. One degree of freedom (the vertical movement of the pelvis) was compensated passively through an ideal spring mechanism and was left free to move without action within certain limits, as shown in Figure 2 e [9]. Impedance control, or resistance to movement, is based on sensing the position of the patient's legs and on the performance of the exoskeleton strength.

NASA developed the G-Trainer^{TM} [10], illustrated in Figure 2 f, which became the first system that uses an anti-gravity treadmill, which was approved by the FDA. By applying this system, the patient may run without supporting his body weight. Therefore, it does not force the joints, ligaments, tendons and muscles. The patient is placed inside a sealed chamber below the waist and wears a neoprene shorts, zipped on the waist. This chamber is pressurized, and an air pressure up, lifts the patient and suspends him above the surface of the treadmill. This lifting force is known as the Advanced Air Pressure Differential Technology (ADAPT). Adjusting the pressure inside the chamber controls the patient's weight.

2.2. *Feet Manipulators*

A major problem in rehabilitation and motor learning is learning gait transition, i.e., to switch between different types of gaits. In order to achieve gait transition, one has to train different types of gait patterns, as well as several occurrences that may arise in daily life, e.g. obstacles. Mobile manipulators feet try to address this problem. Each patient's foot is positioned on a manipulator that simulates the movement of the foot during the stance and swing phases of locomotion. The idea of this machine is to provide gait training guided bilaterally and distally. In addition, the patients' knees are not fixed, such that therapists can physically correct the knee movement, if necessary.

The group Mechanized GaitTrainer developed the GaitTrainer [11], which employs a crank and a gear system connected to a handler. The overall system provides for a lower limbs movement similar to what occurs during elliptical training (Figure 3 a). A unique degree of freedom drives the leg and produces a particular gait pattern, and the center of mass position is controlled in vertical and horizontal directions. Besides, the patient effort is adjusted according to his improvement.

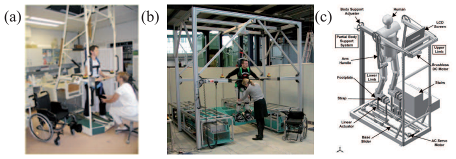

Figure 3. (a) GaitTrainer. (b) HapticWalker. (c) Robot schematic with 6 DOF.

Later, this same group extended this device to another in which movements can be programmed, and developed HapticWalker [11]. HapticWalker, depicted in Figure 3 b, is the first device with six degrees of freedom that may be applied in different type of grounds. Since this device is not attached to the treadmill, the patient may train arbitrary motion trajectories similar to those that are practiced on a daily life. The dynamics of HapticWalker allows smooth movements of the feet in moderate walking speed, as well as realistic simulation of walking speeds in excess of 120 steps /min [11].

Compared with GaitTrainer, the HapticWalker presents some advantages. The trajectories of HapticWalker are freely programmed, so that training is not restricted to walking on level ground, i.e, the patient can train to climb stairs, walking on slopes, etc. Another advantage is to have sensors underneath the manipulators, which record the strength of the patient. This data is then used to perform a training analysis, and allows a rigorous and careful monitoring of the therapist a posteriori. Disturbances may also be added, such as tripping, slipping, and is also possible to integrate it into a virtual environment [12].

Another study [1] also implements the adjustment of the walking speed of patients with the use of feet manipulators and reproduces the effect of different ground types, like the previous device. However, this study takes into account a new observation, which is often overlooked in most robots for rehabilitation: the interaction of the lower limbs with upper limbs. In the human body, there is coordination between arms and legs. When humans walk, both upper and lower limbs move synchronously. Several studies have been conducted around this synchronization and showed that there is a connection between the muscle activation of the arms and legs.

The robot described in [1] and showed in Figure 3 c consists of a feet manipulator with three degrees of freedom in the sagittal plane of each foot; two actuators attached to the manipulators through a rotation joint; a device for the upper limbs; and a partial weight support. The actuators generate spatial movements of the heel along the Y-axis. For the motion along the X- axis, the system employs a sliding mechanism with one degree of freedom. The slippers are connected to a timing belt that is controlled by an AC servomotor. This ensures that foot move in anti-phase. The device of the upper limb is connected via a pendulum link with a prismatic joint to the feet manipulators, such that all members are connected through a pattern of synchronized motion. An adjustable belt provides for a simple and adjustable support system of the patient. This system prevents the patient from falling forward or backward, and also helps to keep him focused.

2.3. Orthoses

The devices that use a treadmill or manipulators are a good alternative to help terapists during the rehabilitation training but they are not useful in situations that a change of direction during the training is required. A lot of patients can benefit with training if only the velocity is changed, but others may need a greater variety of changes. Another important aspect is that these devices do not provide active assistance to the ankle, and also depend on the hip and knee assistance to induce a gait pattern. This may represent a major limitation to these systems, because the ankle supplies more energy than the hip or the knee, during the normal gait. If patients cannot perform the gait patterns with a push-off using the power of the ankle, they are susceptible of learning a compensatory gait, instead of a normal gait, as intended [13].

To overcome these limitations, several studies have been conducted [13] in order to find a solution that required less help from the therapist but could reproduce a wider range of locomotor tasks. From these investigations resulted the orthosis, which are intended to offset the loss of mechanical function and work together with the movements of the patient.

The orthosis is a portable tool that facilitates motor recovery, allowing patients to practice the gait on the ground. For that goal to succeed in rehabilitation, the orthoses must be given energy in order to promote a dynamic gait.

A major problem of construct portable devices is that they require actuators and batteries that need to be light and to have a high capacity to provide power for many hours of use. Fortunately, with the advance of the technology the controllers are more and more robust and the actuators are lighter. Moreover, both the control strategies and the algorithms for these portable devices should be robust and secure to human interaction. Furthermore, the orthoses have been under discussion as to whether they may have a problem of neuromuscular recruitment, promoting the patient's passivity during the training [13].

Some of the first works related with energy-powered orthoses date from the 70s. Miomir Vukobratovic, Yogoslavia, created one of the most advanced models of that time [14]. This device used pneumatic actuators on the hip, knee and ankle, to provide assistance on the frontal and sagittal planes. Through many tests, it was proven that this device was comfortable and it was able to assist a slow gait. With the emergence of actuators, sensors and processors increasingly small, the orthosis began to become a clinical reality.

The director Yoshiyuki Sankai and his colleagues of Cybernics Laboratory at University of Tsukuba in Japan, developed an electro-mechanical powered orthoses called HAL (Hybrid Assistive Limb) [15], which is illustrated in Figure 4 a. The leg structure of HAL enhances the flexion/extension of the hip and knee joints through a DC motor with a harmonic unit placed directly on the joints. The degrees of freedom of the extension and flexion of the knee are passive. The device interface with the patient has the following components: a special shoe with force sensors to measure the ground reaction, armor along the leg until the thigh, and a wide belt at the waist. The HAL system uses a series of sensing components for motor control: surface EMG electrodes placed below the hip and above the knee, potentiometers to measure the angle of joints, force sensors, a gyroscope and an accelerometer to estimate the patient's posture. These sensors constitute the inputs of the two control systems: EMG and gait system. The two together deter-

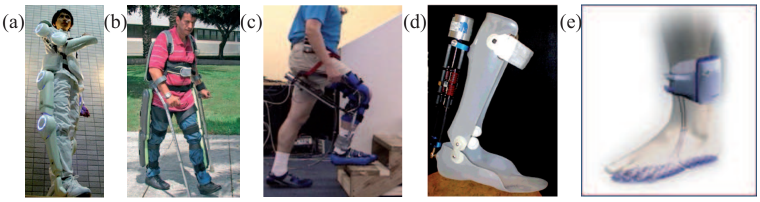

Figure 4. (a) HAL, (b) ReWalk$^{\text{TM}}$, (c) RoboWalker prototype, (d) Ankle-foot orthosis (AFO) by MIT and (e) SmartStep$^{\text{TM}}$ by Andante Medical Devices, Ltd.

mine the patient's intention and perform the gait process. When the patient tries to move, nerve signals are sent from the brain to the muscles through the motor neuron, moving the whole skeletal muscle. According to these signals, a joint is controlled to move with the necessary and appropriate torque at the same time as the patient's muscle. With this, HAL is the first robot that is controlled by a hybrid system (neuronal and motor) [15]. The HAL is currently being marketed in Japan by Cyberdyne Tsukuba [16] and is constantly being updated. Right now, contains batteries with a duration of approximately 160 min, a compact power supply and very esthetic design and the total weight of the device is 23 Kg.

One company that has also been marketing a device of this type is the Argo Medical Techonologies. The ReWalk$^{\text{TM}}$ [17] is a device that allows people who use a wheelchair, to stand up, walk and climb stairs. It also allows the participation of the arms with the help of crutches. This device is illustrated in Figure 4 b.

Yobotics, Inc. has also developed a prototype orthosis called RoboWalker [18]. This still is not, however, commercially available (Figure 4 c).

Another type of orthosis under development by the biomecanic group of MIT consists on an ankle-foot orthosis (AFO) [15] and is illustrated in Figure 4 d. This orthosis is being developed to replace Otto BockC-Leg that is currently commercialized by Ossur. The Otto Bock C-Leg [20] is characterized as a passive device. This orthosis of the MIT group aims to help people who cannot control correctly the foot movement during gait, leaving it to simple fall. The device consists on an orthosis with a series of elastic actuators (SEA) being controlled by ground force and sensory information given by the angle of the ankle. Using the SEA, the device controls the impedance of the knee, varying it during flexion in the stance and the extension in the swing. In clinical studies, the AFO showed to be able to increase the gait velocity, reducing the existent poor control of the foot. This device is compact and consumes little power (about 100W) [15].

A company of Israel, Andante Medical Devices, Ltd., reported in 2005 the release of SmartStep$^{\text{TM}}$ [21], a gait training system illustrated in Figure 4 e. The SmartStep$^{\text{TM}}$ consists of three main components: a boot sole that contains a force sensor, a microprocessor to the control unit, and a storage and data analysis software to the study of patient's performance and evolution.

The boot sole of this device measures the applied force on the heel and on the forefoot of the affected limb. The data are received and analysed by the microprocessor that is used around the ankle. The data is also sent to a computer running the SmartStep software, which uses medical records of the patients as an assessment tool and therapy. The control unit can be programmed to provide to patients, in real time through audible indications, his correct or incorrect gait performance, according with the provided program to each patient [21].

3. Conclusion

Currently there are no sufficient and clear evidence to support a finding about the effectiveness of the training assisted by robots in people with spinal cord injuries. This is due to a low number of samples, methodological flaws, and procedures for heterogeneous training. It seems clear however that a proper and intensive training can lead to real improvement and also, that only robot can thoroughly and continuously monitor patients in their daily life. For all this, rehabilitation robotics is for sure a fertile field that requires intensive research since there is still a long way to go before achieving the required flexibility, reliability and portability.

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