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REVIEW

A review in gait rehabilitation devices and applied control techniques

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ABSTRACT

Purpose: The aim of this review is to analyse the different existing technologies for gait rehabilitation, focusing mainly in robotic devices. Those robots help the patient to recover a lost function due to neurological gait disorders, accidents or after injury. Besides, they facilitate the identification of normal and abnormal features by registering muscle activity providing the doctor important data where he can observe the evolution of the patient.

Method: A deep literature review was realized using selected keywords considering not only the most common medical and engineering databases, but also other available sources that provide information on commercial and scientific gait rehabilitation devices. The founded literature for this review corresponds to control techniques for gait rehabilitation robots, since the early seventies to the present year.

Results: Different control strategies for gait analysis in rehabilitation devices have been developed and implemented such as position control, force and impedance control, haptic simulation, and control of EMG signals. These control techniques are used to analyze the force of the patient during therapy, compensating it with the force generated by the mechanism in the rehabilitation device. It is observed that the largest number of studies reported, focuses on the impedance control technique. Leading to include new control techniques and validate them using the necessary protocols with ill patients, obtaining reliable results that allows a progressive and active rehabilitation.

Conclusions: With this exhaustive review, we can conclude that the degree of complexity of the rehabilitation device influences in short and long-term therapeutic results since the movements become more controlled. However, there is still a lot of work in the sense of motion control in order to perform trajectories that are more alike the natural movements of humans. There are many control techniques in other areas, which seek to improve the performance of the process. These techniques may possibly be applicable in gait rehabilitation devices, obtaining controllers that are more efficient and that adapts to different people and the necessities that entail every disease.

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➤ **IMPLICATIONS FOR REHABILITATION**

- Rehabilitation helps people to improve the activities of their daily life, allowing them to observe their progress in the functional abilities as the months pass by with intensive and repetitive therapies.
- There is a mobility issue when the patient needs to move to the hospital or to the laboratory, which is not always feasible. For overcoming it, patients use the equipment at home to perform their daily therapy. However, they need the sufficient knowledge about its operation, also about the therapeutic movements, the therapy duration and the movement speed. Besides, is necessary to place the equipment in a proper and lively environment that helps to forget or reduce pain while the patient moves his joints progressively.
- The purpose of robotic rehabilitation devices is to generate repetitive and progressive movements, according to the motor disability. There are training trajectories to follow, which motivate patients to generate active movements. The benefits of robotic rehabilitation depend on the ability of each patient to adapt to the speed and load variations generated by the device, improving and reinforcing motor functions in therapy, especially in patients with advanced disabilities in early rehabilitation.
- Multi-joint rehabilitation devices are more effective than single-joint rehabilitation devices because they involve a higher number of muscles in the therapy. The greater the number of degrees of freedom (DoF) of the device, it cushions its effect in the patient because the inertia is reduced and higher torques are generated.
- The assistive technological devices allows to explore different rehabilitation techniques that motivate the patient in therapy, increasing appropriately the energy and pressure in the blood which is reflected in gradually recovering his ability to walk.

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Introduction

Gait analysis studies the human walking in the oscillation phase, which starts at the moment in which one foot is separated from the ground and moving forward, until it touches the ground again, turning into the phase of support [1]. Gait characteristics influences aspect such as force, the centre of gravity, mass and posture [2]. Movement of the body influences the activation and the speed of cerebral blood flow, which is why it is important to keep the limbs active through muscular stimulation [3].

In order to analyse gait from a clinical and scientific perspective, contact and non-contact methods are used [4], helping physiotherapists to detect flaws or abnormalities in gait disorders and human mobility [5]. It takes into account the speed and length of the stride and the gradual cadence in the gait cycle [6]. The contact method refers to sensors positioned in the patient's body or in the rehabilitation device, providing the user with quantitative information regarding the movement (routine or trajectory) of each patient [7]. The non-contact methods refer to the use of cameras with reflective markers positioned in the human body. The infrared light reflected by the markers is captured by the cameras, with the aim of analysing the position of the lower limbs of patients during gait [8].

The locomotion problems are different for each person, and the treatment intensities differ depending the patient and the time it takes with the disease, which makes very difficult to control his movements [9]. They can be caused by many factors, which are analysed by the therapist trying to rehabilitate the gait [10]. There are very common diseases that affects the human gait, such as spinal cord injury (SCI), cerebral palsy (CP) and stroke patients (SP). They have been reported in many papers for validating rehabilitation devices, and their corresponding control strategies or theories in the patient recovery process [11,12].

Most of the rehabilitation robots are adaptations of industrial robots, due to its great breakthrough they have had for controlling their processes [13]. Rehabilitation robots are evaluated to know its effectivity on therapy [14] and can be used in patients with an injury or neurological disorder, without causing additional problems. Different rehabilitation devices were developed four decades ago by engineers and medics [15], all with the purpose of helping patients who need to rehabilitate any part of their body [16]. Besides, in a certain way, they help the therapist to support the weight of the patient [17].The robotic orthoses lead to progressive mobility [18] and combined with regular physiotherapy, they provide encouraging results to patients and therapists. Through control strategies and control techniques, it is possible to manipulate the robotic devices used in clinical gait rehabilitation [19].

Existing rehabilitation devices [20] may be active, passive or hybrids, for upper and lower limbs, as described in Figure 1. The active devices are characterized by having electromechanical mechanisms that help the patient to follow a trajectory defined by the therapist through a human–machine interface (HMI) or with predefined routines. It helps each patient to recover part of the lost movement, but without performing any type of active movement. Passive devices do not have electromechanical devices and this is where all the effort falls into the patient, stimulating him to use his force through active movements. Hybrid devices are those that take into account the patient–device interaction (movement-force) during a trajectory, or simply serving as a guide for the patient, where he applies his own force [21]. These devices allow passive and/or active exercises.

The best selling commercial gait rehabilitator and trainer for clinical patients is the Lokomat [11,22]. It allows to visualize and monitor the progressive therapy of a patient, previously

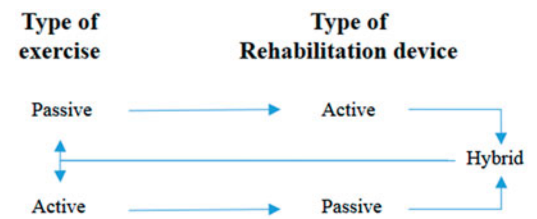

Figure 1. Interaction between patient and rehabilitation device.

configured [23]. The therapeutic movements imitate non-pathological human gait through motion control techniques, for example, fuzzy logic (FL), artificial neural network (ANN) and genetic algorithm (GA). Each of them have their own characteristics, advantages and disadvantages [24]. These artificial intelligence (AI) tools tend to imitate the human brain behaviour, based on reasoning from rules or acquired knowledge [25]. Besides, AI techniques are more popular and they are being implemented in many applications for performing tasks and solving problems [26].

In this article, we present a review of the applicable control techniques for rehabilitation devices, including the rehabilitator types and control strategies. As well as the control techniques applied in other areas that have potential use in the automation of gait rehabilitation devices. These techniques provide feedback to the therapist but have not been applied yet in the automation of rehabilitation devices by considering the ability to move of each person.

This paper is divided into seven sections. Second section presents an introduction to the type of alternative and augmentative robotic devices for hip, knee, ankle or full gait. Third section presents the relevant characteristics of passive rehabilitation devices, while fourth section, addresses relevant information on active robotic devices and their implemented control strategies. Hybrid rehabilitation devices, their strategies, and control techniques are present in fifth section. A discussion on some problems and further challenges in this field, is shown in sixth section. Finally, we conclude and propose future works to research in seventh section.

Types of rehabilitation devices

Gait analysis refers to movement measurement through sensors [6] (cameras [27], inertial sensor, and so forth) located in the human body, in the rehabilitation devices or externally. They provide quantitative information on human locomotion as a clinical objective [28].

There are different types of gait rehabilitation devices which are basically summarized in two large groups: alternative and augmentative devices [29]. The alternative devices, are used in case of total disability or reduced mobility. They do not generate exercises for the affected extremities, for example, wheelchairs [30,31] or autonomous special cars (Figures 2(a,b) correspondingly). The augmentative devices are used by people with reduced mobility [32,33] but that can generate movements or exercises that are useful for their rehabilitation, for example, Lokomat (Figure 3(a)) and Lopes (Figure 3(b)).

The walking speed and the method used by the rehabilitator are important indicators in each of the diseases. However, the best rehabilitation treatment has not been yet determined, it depends on experience and medical decision, requiring a series of tests to determine it [34].

The treatments require as many repetitions, intensity and duration according to a specific patient, by activating their muscles and attempting to rehabilitate their limbs. Schwartz and Meiner [35] said that there are treatments that are beneficial for the

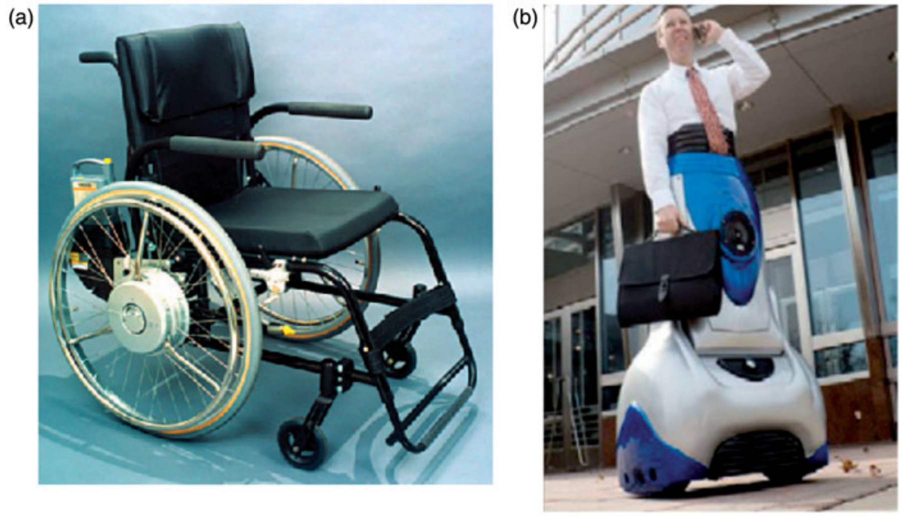

Figure 2. Alternative devices: (a) Hybrid wheelchair with a magnet dc motor [34] and (b) especial cars [35].

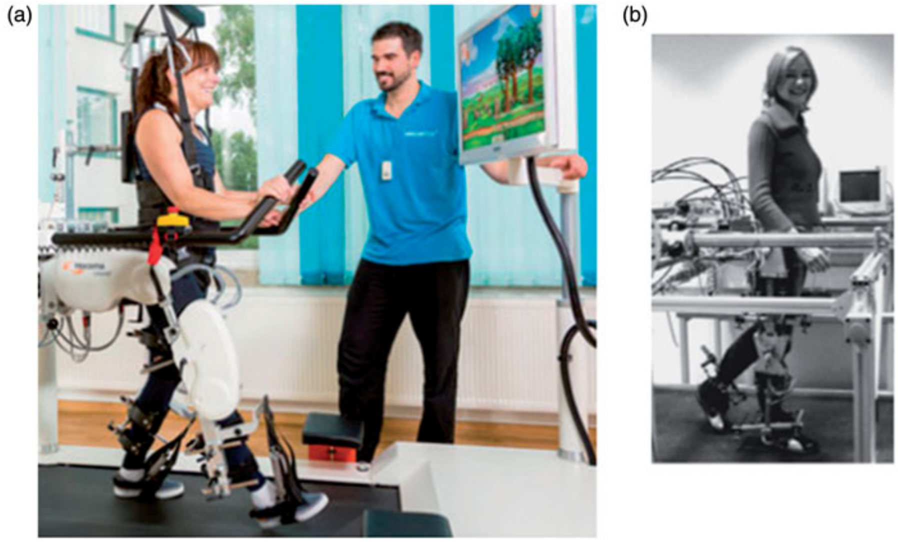

Figure 3. Augmentative devices: (a) Lokomat [36] and (b) Lopes [37].

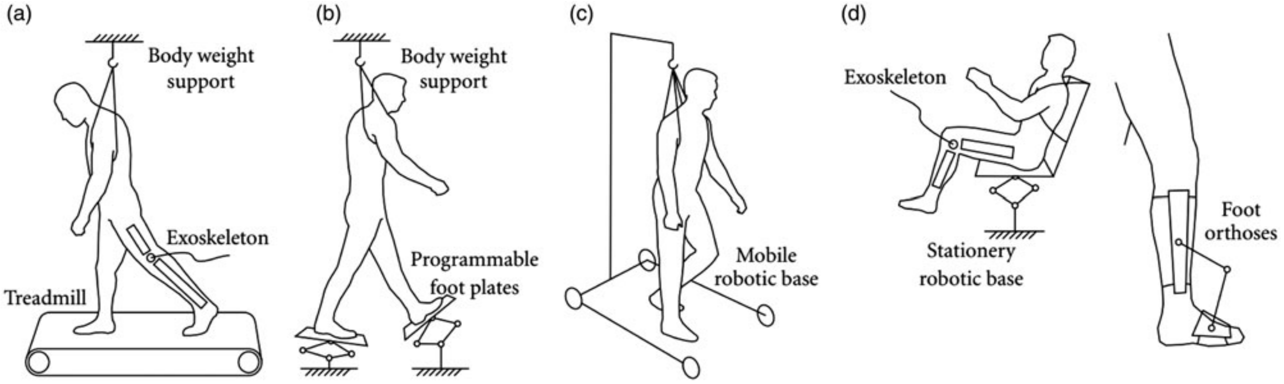

Figure 4. Robotic devices for lower-limb rehabilitation described by Díaz, et al (2011): (a) treadmill gait trainers, (b) foot-plate-based gait trainers, (c) overground gait trainers, (d) stationary gait and ankle trainers, and (e) active foot orthoses [45].

ability to walk; however, there are technical limitations for its implementation.

R. A. Brand [36], commented about the cost-effectiveness in each treatment and its results. These treatments are based on passive and active exercises helping patients to recover mobility [37]. There are lots of exoskeletons and rehabilitation devices for a specific purpose, in both commercial and academic fields, fitting for humans [38] or for animals [39], as in Figure 4.

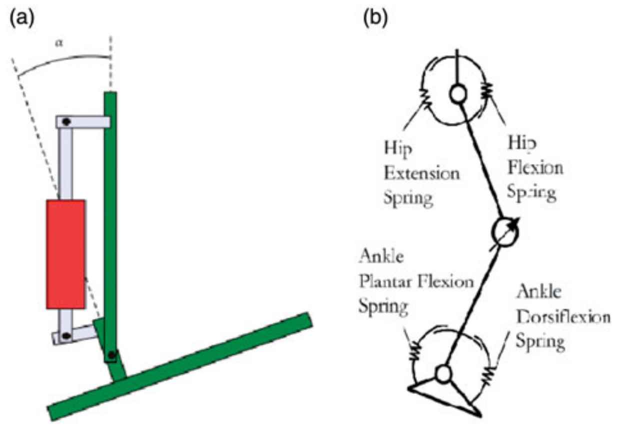

Figure 5. Passive devices: (a) Halmstad University AFO with fluid damper [61] and (b) passive leg of slow walk [62].

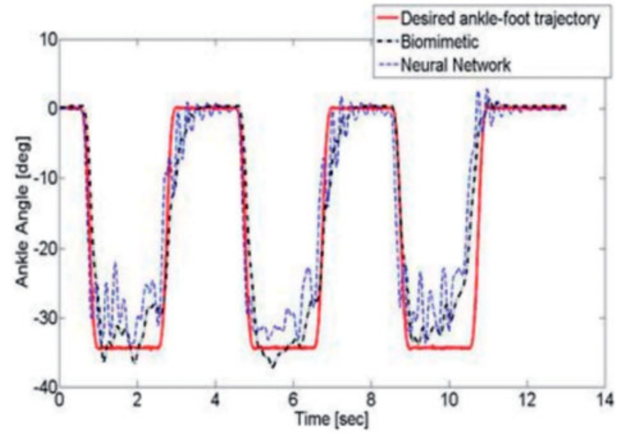

Figure 6. Prediction both biomimetic and NN control of ankle joint position [66].

However, there are other exoskeletons that are used for military applications or heavy loads [40], but are not of interest for this article.

Rehabilitation helps people to improve the activities of their daily life, allowing them to observe their progress in the functional abilities as the months pass by with intensive and repetitive therapies [41]. There are different implications for the rehabilitation of a patient involving not only the therapy; there is a mobility issue when he needs to move to the hospital or to the laboratory, which is not always feasible. For overcoming this issue, patients are advised to use the equipment at home to perform their daily therapy. However, they need the sufficient knowledge of both the operation of the equipment and about the therapeutic movements [42]; also about the therapy duration and the movement speed; it is also necessary that the equipment be placed in a proper and lively environment that helps to forget or reduce pain while the patient moves his joints progressively [43].

The purpose of robotic rehabilitation devices is to generate repetitive and progressive movements, depending on the motor disability [44], there are training trajectories to follow [45] which motivate patients to generate active movements [46]. Implications of robotic rehabilitation depend on the ability of each patient to adapt to the speed and load variations that are generated with the device, improving and reinforcing motor functions in therapy, especially in patients with advanced disabilities in early rehabilitation [47]. Multi-joint rehabilitation devices are more effective than single-joint rehabilitation devices because they involve a higher number of muscles in the therapy. The greater the number of degrees of freedom (DoF) of the device, the effect of the patient is cushioned because the inertia is reduced and higher torques are generated [48]. The assistive technological devices allows to explore different rehabilitation techniques [49], that motivate the patient in therapy, increasing appropriately the energy and pressure in the blood [50], which is reflected in gradually recovering his ability to walk [51].

Passive rehabilitation devices

Passive devices are mainly composed of links and springs, avoiding the use of electromechanical actuators [52]. These devices are used when patients can perform their own movements, that is, active exercises. The users try to move their lower limb following a previously defined trajectory according to their capabilities [53]. However, there is no feedback of the force with which the movement of this limb is performed, so actuators are needed to generate the missing force of each patient and have control of it. Figure 5(a) shows an ankle foot orthotic (AFO) [54] for ankle rehabilitation by using a resistive force. A low-weight portable orthosis for assisting in gait rehabilitation, allowing patients to walk normally, without generating effort and discomfort is shown in Figure 5(b). Its springs can be manually adjusted depending on the assistance required for each person [55].

Aoyagi et al [63], designed a pneumatic robot for patients with SCI. But, due to the error rate in the therapy of each patient, it was necessary to implement a control algorithm to help to correct these trajectories in real time, increasing the use of rehabilitation with assisted therapy. Pelvic assist manipulator (PAM) [64], and pneumatically operated gait orthosis (POGO) [65], are passive rehabilitation devices which allows the patient to perform natural movements without restrictions. It assists in the oscillation phase of the legs modulating the patient's strength, where the control algorithm is feedback by the threshold in the pedal of the device by modifying the speed of each trajectory. This PD control technique is validated in PAM and POGO recording the trajectory to follow while the device's force value approaches to zero, controlling the speed of therapy and synchrony of each step.

In the passive foot-ankle prosthesis presented in [66], the controller predicts the movement of the patient in a defined trajectory using EMG signals, keeping in mind that there is a muscular variation from person to person. The dynamics of a force-velocity model based in the position, velocity and angular acceleration, corresponding to an ankle-foot trajectory. Samuel Au et al [66], obtained natural movements in the sagittal plane, based in a biomimetic model of the human ankle-foot system using a multilayer neural network and a standard back-propagation algorithm, as in Figure 6. The model considers the EMG measures of the gastrocnemius, soleus and anterior tibial muscles. These data is not feedback into the neural network in real time, making it less efficient.

Gravity balancing orthosis (GBO) do not require electronics, motors or control systems [67]. Its aim is to train the gait of SP and other neuromotor disorders through reconfigurable springs, as in Figure 7(a). The patient performs active rehabilitation and the device serve to aid and supply in the initial move of the user. Figure 7(b) shows the passive rehabilitation device GBO, which includes an HMI screen, remarking that "Mirror-image movement is an important rehabilitation strategy" [68]. Another strategy was proposed by Vijaya K. et al [69], mentioning that patients can activate their weakened muscles with gravity effects in an early rehabilitation.

Mavroidis et al [70], implemented a knee brace for patients with muscle atrophy or nerve damage after some operation, as in Figure 8. It applies electrical stimulation depending on the

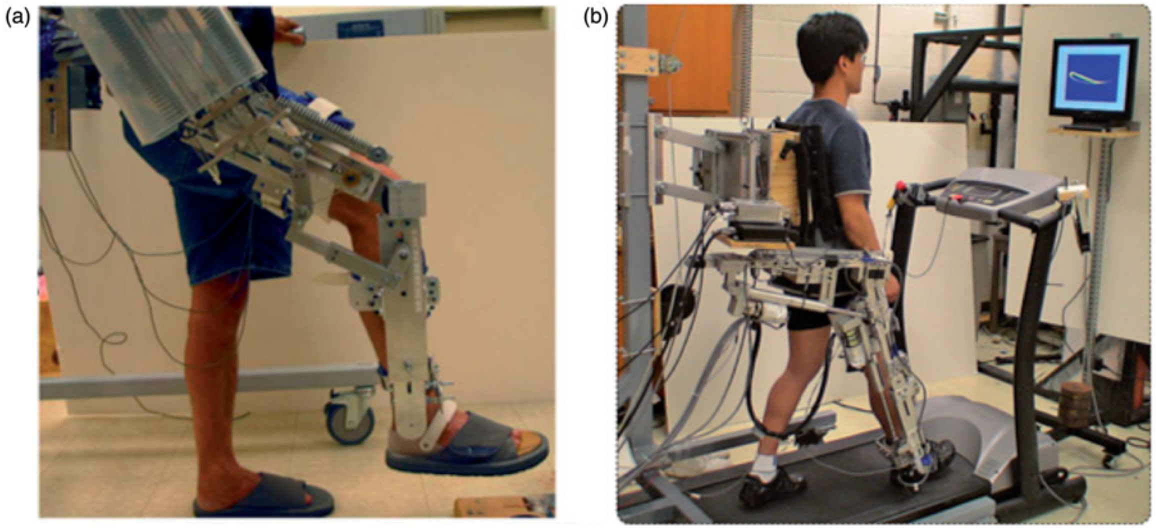

Figure 7. GBO passive exoskeleton: (a) Physical prototype with spring configuration [67] and (b) GBO developed at the University of Delaware [68].

Figure 8. Knee device with electrical stimulation biofeedback [70].

feedback of EMG signals. They include an HMI to visualize the muscular behaviour of the patient through sensors in a controlled environment, avoiding lesions in ligaments, bones and soft tissues, and where the therapist can observe the patient's response to such treatment.

There are many passive robotic devices for assisting in the gait phase, functioning as a guide in patients who can perform movements by themselves without having to be mechanically assisted. The most common control strategy is the position control [71], in which the trajectories are defined by the therapist [13], helping patients to rehabilitate their disease or neurological disorder.

Defining these trajectories becomes a challenge for the therapist, since he must determine the attendance level and the exercises for each patient depending on the evolution of their treatments [56]. For this reason, rehabilitator robots can be used in order to have a better control and feedback of the rehabilitation device and the patient in each therapy.

Active rehabilitation devices

Active devices can be classified into three types: with treadmill, feet manipulators and orthoses [73], as shown in Figure 4. The walking treadmill [74] is useful for generating lateral stability between the device and the patient, who joins its lower limbs with adjustable straps to the device, allowing to make active movements [75].

A feet manipulator, includes different trajectories for different types of gait, similar to those performed by people in daily life [57]. It pushes the legs forward while controlling the position and speed, generating muscle activation. Each part of the device must be adjusted to the anthropological dimensions of each patient, making him feel comfortable avoiding distractions and insecurity [58].

Finally, orthoses are devices that take into account hip, knee and ankle. The ankle is an indispensable part of the gait and is where there is a greater supply of energy, if it is not correctly rehabilitated, the rehabilitation turns to gait compensating more than normal gait [59]. Another important parameter that considers the rehabilitation is the robustness, since the devices are use with people and the quality of their movements must be guaranteed [60].

An exosqueleton developed at Delaware University is shown in Figure 9(a). The device has linear actuators in the hip and knee, a treadmill that helps each patient initiate movements, as well as visual feedback on a screen which allows to monitor the performance in each trajectory [61]. MOPASS Rehabilitation device is a four-wheel mobile platform for gait rehabilitation, it has three degrees of freedom (DoF) for each leg, and an additional rotary DoF in the sagittal plane for the hip. The therapist defines the trajectories for hip and knees in each patient through an HMI, considering the position, speed, and acceleration of each limb [62]. It is presented in Figure 9(b), where it presents in blue the main mechanical parts, in red the active DoFs and in green batteries and computers [63].

Implemented control strategies

Taking into account, the control strategies reported in [13,16,19,71,84–89]. Each one is focused on a specific application for a specific type of pathology in different body parts, as resumed in Table 1. We have considered rehabilitation devices at both the commercial and research levels.

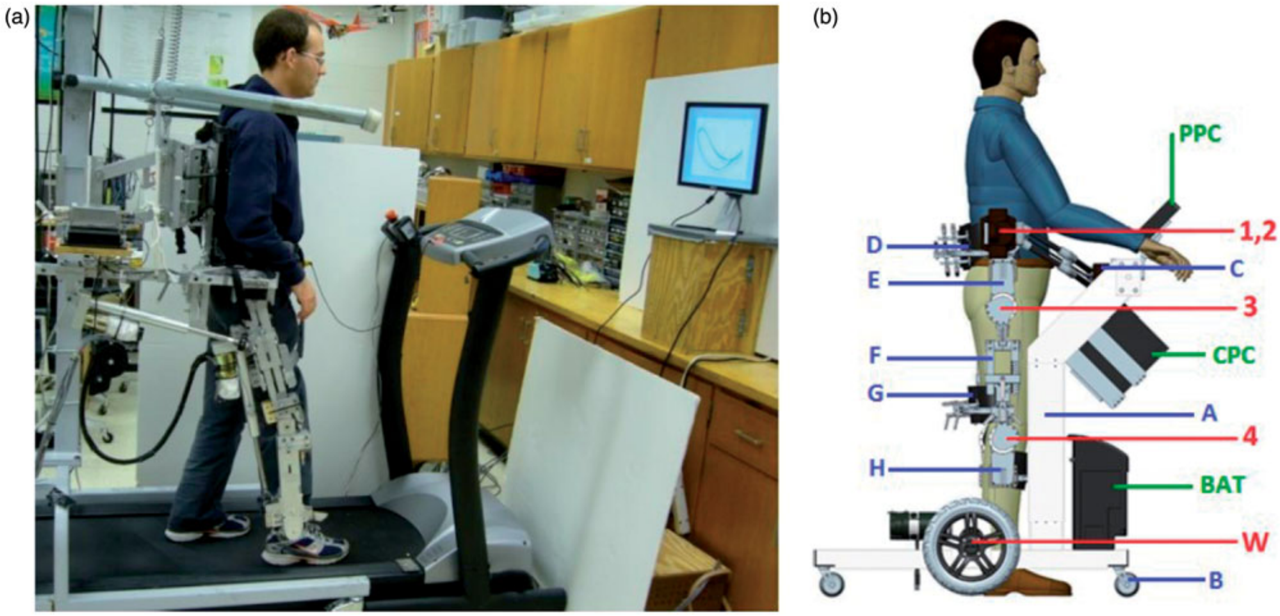

Figure 9. Active devices: (a) Gait training exoskeleton at University of Delaware [83] and (b) Gait Rehabilitation System MOPASS [82].

Table 1. Gait rehabilitation devices with passive exercises.

Rehabilitation device	Application	Pathology or mobility disorder	Control strategies
Lokohelp [73,90]	Posture control, knee extension, foots active impact and active hip extension	Stroke, SCI and brain Injury	Defined trajectories
Robotic Exoskeleton (REX) [89,91,92]	Robot for rehabilitation and exercising. To walk, make turns, climb stairs and slopes	Manual wheelchair users who can self-transfer and operate hand controls	Joystick interaction
ReWalk [93]	Knee motion and powered hip	SCI	Mimics the natural gait pattern of the legs, using a HMI
AutoAmbulator or ReoAmbulator [94,95]	Lower-limb rehabilitation therapy	Walking disabilities	Position control using a HMI touch screen
Virtual Gait Rehabilitation Robot (ViGRR) [96]	Gait rehabilitation	Post-stroke victims	Defined trajectory, patient joint kinematics and dynamics. Used a HMI

The reported studies have implemented at least one control strategy during the development of their research to monitor the therapy evolution, using sensor feedback and motor control. Among the various control strategies that researchers have implemented, the most common are position and strength control analysing kinematics, and dynamics of the mechanism and the human body, by monitoring muscle activation with EMG. In many cases, these are inputs for the controller of the rehabilitation device, depending on the physical activity that the patient can perform [97]. Studies report that passive exercises with active rehabilitation devices helps the patient in the recovery stage with defined trajectories, reducing muscle atrophy and correcting the movements gradually [21].

Freivogel et al. created Lokohelp [98], an electromechanical gait device for evaluating the repetitive locomotion training and the comfort of the patient in it, through different control strategies, randomly selected. This device varies its velocity between 0–5 Km/h, determined by the therapist and previous studies for each patient. It is important to note that the results show differences with the Gait Trainer (GT1) and Lokomat, benefiting training therapy independently if performed with an electromechanical gait assisted device.

Hybrid rehabilitation devices

In fourth section, we observed robotic devices that assist in the training of human gait, moving the limbs of patients following defined trajectories, allowing the patient to experience a "normal" movement pattern, but without generating movements by themselves. Hybrid robotic devices allow interaction between the patient and the rehabilitator during a certain time of therapy, allowing passive and active exercises as shown in Figure 1.

The interest in creating devices for assisting in gait rehabilitation where the active participation of the patient and the feedback of his progress has been increasing in the last years. A great part of these devices have been proved in healthy patients, given that its validation in a clinical setting is very complicated [72,99–101], so as the positive or negative effects of assisted training [16]. These devices allow the patient to experience different mobility patterns, helping his nervous system to learn trajectories [102]. The control strategies implemented in the rehabilitation devices must coincide with the therapeutic objective, understanding each of the specific recovery tasks. In patients with mobility problems, is very complex to perform diagnoses, so an important control strategy is the use of EMG signals as feedback. These signals are useful for interpreting human muscle activation, from which the device can take decisions about the assistance level, based on previous training by the therapist [103].

Adaptive control with EMG signals anticipates the patient's intention of moving after exceeding a certain threshold, indicating to the motors the amount of assistance they must apply, making therapy challenging for control [71]. The EMG signals are analysed with neural networks and neuro-fuzzy algorithms, especially for upper limb. There is few research reported for the lower limb using EMG signals throughout the therapy work cycle, providing considerable amounts of data to be analysed [104].

Through haptic interfaces [105] or virtual reality [106], it is possible to observe both, the position of the patient in the current rehabilitation, and the objective to be achieved with it. Taking into account the interaction of the patient by applying resistive forces in the foot of each patient and thus defining the mechanical interaction [107].

Clinical rehabilitation devices are designed to perform smooth movements, with minimal inertia, impedance and friction, but which react quickly to the motor needs of each patient [102]. To accomplish this, sensors are placed in both, the device and the patient in order to have control of position, speed and force in the patient–device interaction. Each action is visualized in an HMI, implementing progressive algorithms that feedback on the human movement, improving the performance of the assisted therapy [108]. Two important aspects are taken into account when talking about rehabilitation devices, the mechanical part and the control system [109]. The mechanical part includes the type of motors that are implemented to assist with specific characteristics, that is, speed, inertia and maximum support force [110]. Control systems or high-level controllers must meet a number of requirements to be used in clinics and hospitals, for example, robustness and safety [88]. These are responsible for phase transitions, interaction and modes of walking [110].

Currently, control algorithms are developed for a specific application based on a series of previously defined characteristics. Depending on the degree of complexity and risk, it is necessary to identify explicit parameters that ensure a robust, flexible and secure control structure [111]. For both the diagnosis and the evaluation of gait events, the amount of data available for the algorithms is very important. With this data, a system can be flexible enough when new conditions are introduced, without reaching an overfitting condition of the models [112].

In the beginning, Lokomat used control strategies for realizing only passive exercises [113]. Since 2005, it includes control strategies to allow the patient's interaction in therapy accelerating their progress. The first step is to implement an adaptive control algorithm that reduces torque allowing the patient to apply his own force in the movement. It then applies an impedance control (Figure 10) to reposition the patient's legs to the initial trajectory allowing the patient to walk freely. With this control technique, there is a delay of 15 ms in the detection of foot events and 30 ms for the heel, that do not interfere in the rehabilitation. Bernhardt et al. [113], used the impedance control, in which the patient must have considerable force at the time of making the movements. It is not suitable for patients with total loss of movement in their lower limbs.

Physiotherabot [21] can perform abduction–adduction for the hip, and flexion–extension for the knee and hip. It was targeted for gait rehabilitation in patients with SCI, stroke, muscle disorder and after a surgical operation. It implements an impedance control for position and force, and it is configured though an HMI which receives relevant patient information and the type of exercise to be performed. This device implements active, manual (passive), isometric [114], isokinetic [115] and isotonic [116] exercises, which can be modified by the therapist depending on the feedback received from the sensors (force/torque and position).

Akdogan et al. [117], designed a knee rehabilitation device with servomotors and sensors; It includes an HMI that feedbacks to the therapist: the initial position, patient reaction force $F_{reaction}$, torque τ, desired position $\theta_{desired}$ and the force F applied by the robotic device. They implemented an impedance control that is adjusted through 70 rules, depending on the external force applied by the patient to define the trajectory, as in Figure 11. The system learns the trajectories, position, and strength of each movement performed by a physiotherapist in teaching mode, with a sampling of 1 ms. It then acts in therapy mode based on the parameters previously saved.

Ye, et al [118], developed a gait rehabilitation device that executes force assistance automatically, consists of a body weight support (BWS) unit and active mobile platform. The first level of control is based on admittance for speed controlling, where the maximum speed is a function of the patient-device interaction. As in LOPES, it can adopt two modes of rehabilitation, patient-in-charge and robot-in-charge. The second level of control is based on following a trajectory where its amplitude depends on the force sensors. The operation of this adaptive control algorithm and its feedback stage is shown in Figure 12. Experiments were performed in three healthy patients, supporting 10% of the weight of each patient with the rehabilitation device, and their gait and force were analysed in the analysis and research phase.

To validate the feasibility of considering the ankle in the rehabilitation of gait, an adaptive impedance control is implemented in Anklebot [119]. Each of the parameters is gradually modified according to the progress of each patient, visualizing a

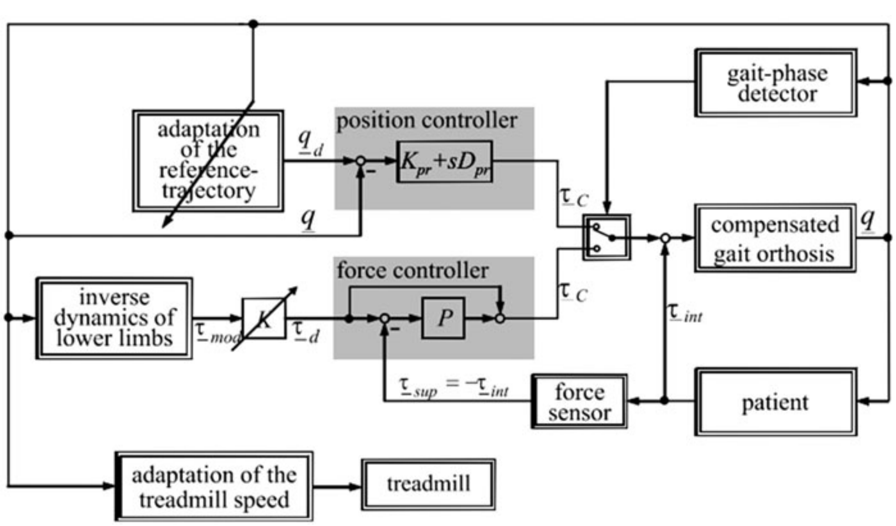

Figure 10. Impedance control for force and position of Lokomat [113].

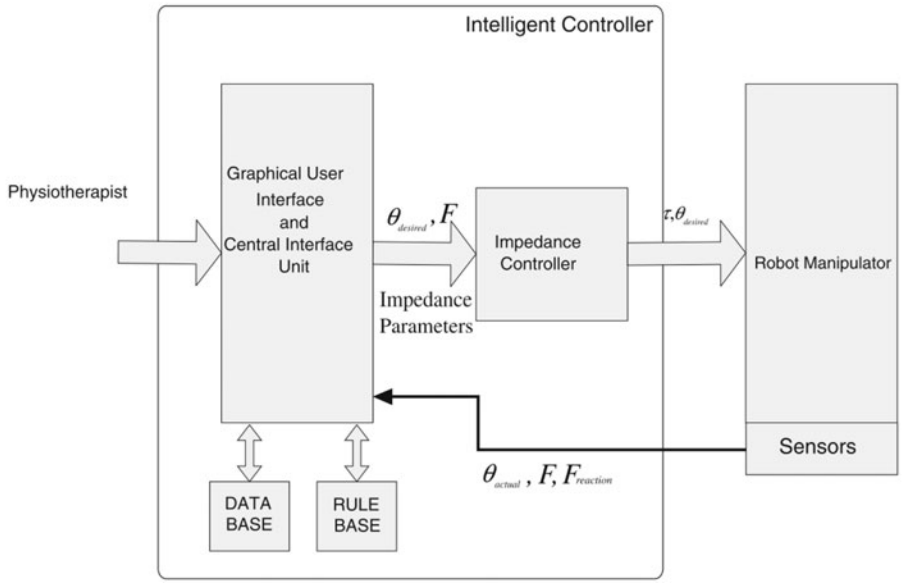

Figure 11. Intelligent impedance control [117].

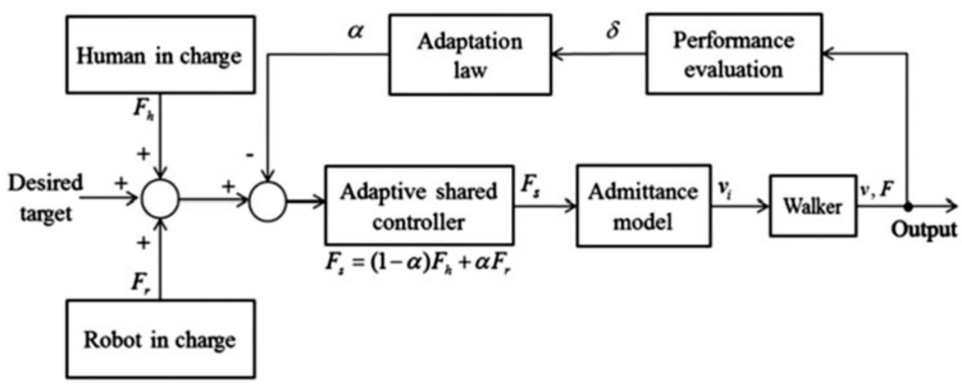

Figure 12. Control algorithm of gait rehabilitation mobile device [118].

robust Anklebot drive to various disturbances generated in the ankle of the patients.

Aguirre et al. [120], proposed a new method to work with impedance control, which was called compensation controller. It consists in a virtual environment in which they can modify the movement speed of the pathological and non-pathological patients. They take into account the dynamics of the rehabilitation device, the muscular torque and musculoskeletal modelling of each patient. They used the negative damping instead of the natural one for the dissipation of the generated energy, trying to reduce the average time of movement, considering the dependence of the damping in the speed, doing almost zero the forces of interaction at resting [121].

A robotic device that implements control strategies for balancing the patient-robot force is implemented by Simon et al. [122]. The person extends his legs applying a certain force, depending on the resistive load configured in the HMI, based on the symmetry of the legs as shown in Figure 13. Validation was performed with non-pathological patients, performing two experiments. During robotic assistance, the movements were safe and uniform; when disabling attendance, the movements were no longer symmetrical and progressive. The patients applied more force due to their healthy condition; however, in patients who are ill or have lesions, the tests must be different because of their reduced movement condition, avoiding to cause subsequent injuries.

Table 2 shows the rehabilitation devices that implement control strategies that considers the patient's interaction during therapy. It also presents the application for which the device was designed, the pathology or mobility disorder to be rehabilitated, the implemented controller, DoF of the device, the technical information about the actuators, the maximum rehabilitation speed allowed by the device, and some relevant data, for example, system feedback. Is important to note that these treatments are performed in patients therapeutically evaluated, ensuring that the suggested movements or "non-voluntary" exercises will not harm the patient [123].

The speed of the therapy will depend on the mobility of each patient, in this sense, a speed control technique is necessary to allow the patient's muscle to be exercised, demanding a higher speed range while the therapy progresses [124]. Each person has a range of normal walking speed that varies depending on the age, weight and height, specifically [125]. The walking speed of a healthy person is in the range of 4.5–4.9 km/h [124].

Impedance control [126] is based on strength and position control strategies and is the most used control technique in both lower [127] and upper limb rehabilitation devices [16]. In this case, the mobility of the patient is measured in a previously defined task, demonstrating positive results in the muscular recovery of the patients [108,128].

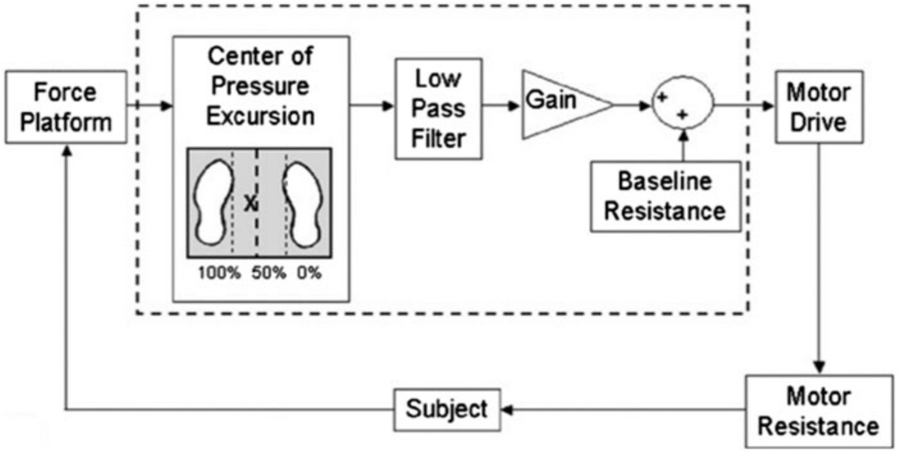

Figure 13. Robotic force lower limb platform, processing data and adjusting resistance in real time [122].

Banala et al. [102], presented different simulations for controllers that could assist in gait rehabilitation in SP. A first controller is based on following a predefined trajectory in a certain time. The second controller is a closed-loop PD controller with a finite number of parameters. Finally, the third one is based on a foot force controller, aiming to provide cushioning (minimizing oscillations) and creating a force field around it, using feedback by encoders and force-torque sensors. The linear motors use a friction model controller, in which the previously obtained data and the load in the endless screw are considered in a proportional-integrative (PI) fast controller, obtaining in this way better results in the simulation.

Different control algorithms for detecting gait events in healthy patients on the treadmill are compared in order to determine the most suitable model for knee and foot. Galván-Duque, et al [103], reported that NN have the best performance for non-linear data in applications with high-frequency components. For low frequency, the linear models OE (Output Error) and ARX (Autoregressive Models with Exogenous Variables) are used. ANFIS (Artificial Fuzzy Neural Inference Systems) becomes an attractive tool to explore, where it combines a Fuzzy Inference System with a NN. This work uses three Gaussian membership functions for the heel foot switch input and for the toe foot switch input; for the knee angle input, it uses eight Gaussian membership functions, in 80 epochs and with constant output.

Boian et al. [148], performed experiments with repetitive exercises using a virtual reality environment for adults and children [149]. They used the Rutgers Ankle platform for ankle rehabilitation in SP, giving to the rehabilitation another therapy approach based on haptic feedback, where users are seated and participate actively. The therapist is able to change the routines in real time for visualizing the evolution of each patient. Haptic environments vary from flying an airplane to navigating a boat. In the first, one can follow any trajectory, while in the second the trajectories are limited and with external forces driving the patient to orient his ankle in one direction by applying his own strength, increasing the energy generation in the lower limbs (ankle) of the patients [150].

A neuro-fuzzy control for an upper limb rehabilitation device in which the patient's EMG signals are used to take action on the rehabilitator device is presented in [151]. It is very difficult to obtain the same EMG signal in a repetitive motion since is highly non-linear, and it must take into account that muscle activity is going to be affected due to the load on the anterior joint of each person. The controller is composed of three stages and uses a backpropagation learning algorithm. According to the muscular activity obtained from each patient, in the first stage, the EMG signals from the upper arm are selected as input for the controller, additionally; it uses force sensors in the wrist when the voltage of the EMG signal is very weak. Considering the different shoulder and elbow positions, four neuro-fuzzy controllers are implemented at the same time in the second stage. Finally, the third stage of the neuro-fuzzy controller defines the assistance level for the upper limb rehabilitator, based on the human movement related with the IF-THEN fuzzy rules [152].

Berkeley lower extremity exoskeleton (BLEEX) [153] includes flexion/extension, abduction/adduction besides hip and ankle movements. It is an exoskeleton whose application is not medical. It was made to transport heavy materials or climbs stairs as shown in Figure 14. It includes an improved robust control for force and position by using inclinometers, which are placed on the patient in a safe and compensatory way. Position control includes torso, backpack, and the leg. A test in a laboratory says that BLEEX can walk with a payload of 18 kg (40 lbs.).

Discussion

Classifying the rehabilitation devices into three groups (passive, active and hybrids), helps to identify the possible exercises to be performed for a specific pathology of each patient, the objective and the characteristics for which it was built. The rehabilitation devices are designed to be used in different stages of therapy, for example, after some surgery or in an early stage of rehabilitation, the patient needs repetitive movements at constant speeds to activate their muscles. They are also useful when there is a significant progress in recovery and the patient can generate movement of their limbs, participating actively in therapy.

Active or passive exercises are used in gait rehabilitation depending on the disease, treatment and therapy intensity that each patient needs. These exercises help muscles to be oxygenated, regaining their function progressively [154].

There are few rehabilitation devices, which considers the patient interaction at therapy, especially for human gait, being one of the main research and commercial objectives. The most common control strategy for this interaction is through EMG signals, as they feed the therapist with the muscular activation of each patient and the intensity of their movements. However, this is a topic that is not fully implemented yet, because the signal is not totally reproducible and there is no reliability in the data acquired [155]. The feasibility of using EMG signals to feedback

Table 2. Hybrid gait rehabilitation devices with passive-active exercises.

Rehabilitation device	Application	Pathology or mobility disorder	Control strategies	Control technique	Degree of freedom	Technical information	Maximum therapy speed (km/h)	Additional information
Lower extremity powered exoskeleton (LOPES) [15,37]	Leg-joints	Stroke patients	Position and forces/ moment, EMG signals	Impedance control	6	Servomotor: maximum speed 8000 rpm to 567 W, continuous torque 0.87 Nm, and peak torque: 2.73 Nm. Sideways motion: maximum speed 6000 rpm to 690 W. Linear motor: peak force 204 N to 250 W	2.7	Achievable bandwidths: 4 Hz for full force (65 Nm), 12 Hz for smaller forces (<10 Nm)
LOKOMAT [11,36,129,130]	Gait cycle	Stroke patients, spinal cord injury, traumatic brain injury (TBI) patients	Position and force, computer- control	Impedance control and conventional PD controller	7	Average torque: 30- 50 Nm to 150 W, maximum peak torques are 120 and 200 Nm	3.2	Ground reaction forces were at 1000 Hz and were filtered in Matlab
[118]	Gait phases	Stroke patients	Velocity, force trajectory	Adaptive control between users-walker. Admittance-based interaction control	6	…	1.8	Force/torque sensor between walker and patient to generate the force trajectory. IMU sensors for gait phase estimation
WalkTrainer [131,132]	Leg trajectories	Spinal cord injury (Paraplegic patients)	Muscle stimulation, position control	PD controllers. Selective compliance algorithm	6	Maximum average torque raw over five complete cycles: hip: 30 Nm, knee: 20 Nm and ankle: 10 Nm	4	Muscle stimulation is in the range of 0–100 mA per channel, with frequency of 30 Hz. Used a Graphical User Interface
G-EO Systems (end effector robot) [23,133]	Gait trajectory	Traumatic brain injury	Position and force control	Task-specific repetitive	6	Programmed trajectories generation in footplates	2.3	Physical therapy: 30 min. Occupational therapy: 45 min. Suitable for wheelchair patients to go up and down stairs and perform repetitive therapy
Gait Trainer (GT) [94,134,135]	Restoration of gait	Gait cycle in healthy patient and hemiparetic patient	Position	Control of the center of mass	7	McKibben pneumatic actuators	4.032	Range of 0 to 140 steps/min
Anklebot [119,136,137]	Gait training	Stroke patients, cerebral palsy	Kinematics and kinetics, position control	Impedance controller with a proportional- derivative (PD) controller	6	Brushless DC motors (Kollmorgen RBE (H) 00714) with peak torque of 0.249 Nm. Increase of met torque to 23 Nm with reduction of gears	1.29	Linear encoders Gurley R19 and Renishaw to position information. Analog current sensors to torque measure
Active Leg Exoskeleton (ALEX) [83,96,138–140]	Moving legs	Walking disabilities, (It will be used for stroke patients)	Force-field controller	Force field and close loop PID controller	7	ALEX II: Kollmorgen ACM22C^2 rotary motors geared with Thomson Micron 1:50 and 1:60 gearboxes in hip and knee joints	…	Range of movement: hip joint ±40°, knee joint 45-60°. Load cells Futek LSB200 with CSG110 to measure the tension in the cables. Used a HMI
Hybrid Assistive Leg (HAL) [88,141,142]	Rehabilitation human gait capacity augmentation	Gait deficiencies and disorder	EMG signals, force control and position control	Phase sequence control with Proportional EMG control	6	DC-motor with harmonic drive and assist torque	6.84	For phase change are set thresholds of 560N and 80N to front and back part of the foot, respectively. EMG signals are amplified 10○6 times, and filtered in a range of 33- 500 Hz
Ekso [68,143–146]	Increased motor and muscular activity	Stroke patient, Spinal cord injury, multiple sclerosis, cerebral palsy and multiple diagnoses	Postural control of weight shifts, feedback with EMG signals	Augmentative and progressive training	6	Powered by motors with cordless power to the device. 2 lithium batteries to move for 4 continuous hours	3.2	A patient can give 308 steps in a therapy heel to toe gait. SmartAssist software in real time (intuitive walking, patient control or therapist control)

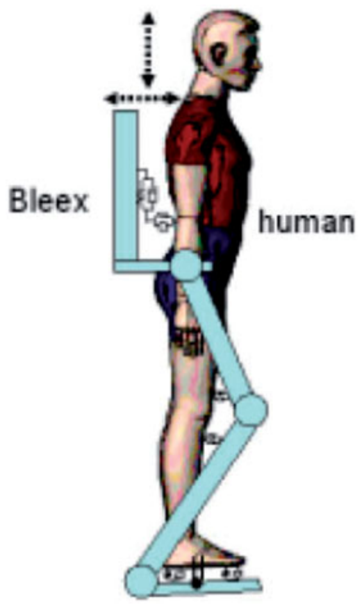

Figure 14. Illustration image between human and BLEEX contact [153].

control systems into rehabilitation devices has been stated [156]. The only limiting factor when talking about EMG signals is the patient's illness, given that for paraplegic patients, it is impossible to use this control strategy, as they do not generate any muscle activity.

A great percentage of the previously mentioned rehabilitation devices have been validate in healthy patients without any motor restraint. However, the purpose of each of these devices is to assist in gait rehabilitation of patients with a specific disease or neurological disorder as can be seen in Tables 1 and 2. But at engineering, a series of permits is required in order to guarantee the medical support, the safety and integrity of each patient, complicating its validation.

Rehabilitation devices to assist in gait therapy such as Lokomat, GT and ALEX, allows seven DoF considering flexion-extension for each joint and abduction-adduction in the hip. While other devices as in Table 2, allows six DoF, eliminating the hip abduction-adduction by attaching the patient to a harness. Providing him with the freedom to generate his own movements.

Most of the gait rehabilitation devices reported in Table 2, handle a walking speed of 1.29 km/h as minimum, and 4.032 km/h as maximum. This speed is lower than a normal walking in a healthy person, which is in the range of 4.5–4.9 km/h. In the case of exoskeletons, is possible to reach higher walking speeds, as the case of HAL, which is a light robotic exoskeleton, which reaches 6.84 km/h.

Many of the works reported here have used different techniques to detect gait events but not for feedback the device and generate movements according to the capacities of each patient. It is necessary to use precise control algorithms to define the appropriate rehabilitation task in each case of neuroplasticity and the corresponding motor learning exercises in each phase of recovery. ANN's are widely used for analysis and classification of EMG signals, but there is a poor use of ANN's for controlling the rehabilitation devices.

The use of advanced virtual reality algorithms makes possible to have an efficient gait rehabilitation, where the patient interacts actively during his rehabilitation. The virtual reality environments were test in ankle rehabilitation, having positive effects in neuro-rehabilitation, without the need for wearables.

In hybrid upper limb rehabilitation devices, more results and better control techniques are reported, especially for the multi-functional control of hand prostheses, taking into account EMG signals as feedback for the system.

The neuro-fuzzy controllers can be applied in gait rehabilitation, since they automatically adapts to the physical and physiological characteristics of each patient, by means of a rule-based system.

Currently, the problems encountered for implementing these control systems are: the computational cost, the high frequency and amplitude of the data, making the system unstable and slow. Fortunately, today computers with advanced software and miniature electronic components are available, to implement and validate different control techniques ensuring efficiency in the assistance.

Finally, it is important to emphasize that the control strategies for gait rehabilitation devices, presents reliable results, as its feedback uses sensor fusion. Ensuring the repeatability of the data by perceiving characteristics of the environment that might be impossible to perceive with the information of a single sensor. However, the rehabilitation devices lack of an intelligent control technique where the system thinks of its own, without the assistance of a physical person.

Conclusion and future research

In this article, the most representative studies related to gait rehabilitation devices were reviewed. It is observed that the largest number of studies reported, focuses on the impedance control technique. Leading to include new control techniques and validate them using the necessary protocols with ill patients, obtaining reliable results that allows a progressive and active rehabilitation. With this exhaustive review, we can conclude that the degree of complexity of the rehabilitation device influences in short and long-term therapeutic results since the movements become more controlled. However, there is still a lot of work in the sense of motion control in order to perform trajectories that are more alike the natural movements of humans.

There are many control techniques in other areas, which seek to improve the performance of the process. These techniques may possibly be applicable in gait rehabilitation devices, obtaining controllers that are more efficient and that adapts to different people and the necessities that entail every disease.

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