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Review Article

# Wearable lower limb robotics: A review

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ABSTRACT

Owing to the recent progress in the field of supportive robotic technologies, interest in the area of active orthoses and exoskeletons has increased rapidly. The first attempts to create such devices took place 40 years ago. Although many solutions have been found since then, many challenges still remain. Works concerning the lower extremities and active orthoses are listed and described in this paper. The research conducted and commercially available devices are presented, and their actuation, hardware, and movements they make possible are described. In addition, possible challenges and improvements are outlined.

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## 1. Introduction

Over the past few years there have been many attempts to integrate the human body and a robot into a single system. The opportunity to develop robots that can serve humans and that can be applied in the field of biomedicine is increasingly being inspired by other disciplines, such as those in industrial fields, for example, systems in which people contribute in the form of intelligence, and then benefit from robotic system's performance, power, and precision, are called user-oriented robots.

Here, we limit the scope of our review of user-oriented robots to those that run parallel to the wearer's lower limbs, which implies robotic leg exoskeletons and active orthoses. Although the described devices are different in terms of their construction, they are made of elements and kinematic coupling engines that either reflect the structure of the human body whose structure is designed around that structure, without containing all of its degrees of freedom.

The aim of this paper is provide an overview of all the efforts that have been made to build lower extremity exoskeletons and active orthoses, which have a wide range of possible applications. These uses include helping patients to guide the trajectory of their movements or repetitive training, providing physical support to ADL (Activities of Daily Living), and facilitating labor-intensiveness by decreasing the load action on the operator. These fields of application form three main groups of powered lower-limb devices: rehabilitative, assistive, and empowering devices.

This paper is organized as follows. Assistive exoskeletons and orthoses are presented in Section 2. Rehabilitative devices for musculoskeletal therapy are discussed in Section 3. Finally, a summary and concluding remarks are given in Section 4.

## 2. Assistive exoskeletons

The aim of assistive robotics is the production of exoskeletons that have sufficient flexibility (both mechanical and control) for performing the wide range movements encompassed in ADL, such as walking, walking up and down stairs, sitting and

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standing up. These devices are intended to be worn by the elderly and those who are physically weak.

Assistive exoskeletons can be classified into full and partial lower limb exoskeletons. The distinguishing criterion is the number of human joints that a device runs parallel to. For example, a full lower limb exoskeleton contains joints located alongside the hip, knee, and ankle joints. Partial lower limb exoskeletons mostly focus upon joints that work together with the knee or ankle joint.

### 2.1. *Full lower limbs*

The development of robotic orthotics began in the 1970s, when Miomir Vukobratovic of the Mihailo Pupin Institute in Belgrade constructed the active assistive lower limb exoskeleton. This hydraulic exoskeleton provided actuated flexion/extension of the hip, the knee and the ankle, as well as hip abduction/adduction. During the same time, Seireg and Grundman at the University of Wisconsin designed and implemented an exoskeleton to facilitate walking forward, sitting down, standing up, and walking up and down stairs. This exoskeleton was also hydraulic. Furthermore, it had active joints at the hips and the knees to support flexion/extension. The rest of the DoFs were either passive or controlled by springs. The desired motion was chosen by the patient by using switches on a control board. The final trajectory of a movement was preprogrammed on the basis of the trajectory of a healthy subject.

Kawamoto and Sankai et al. began developing the exoskeleton HAL (Hybrid Assistive Leg) in the mid 1990s [1]. Their first prototype had active joints with 1 DoF at the hips and the knees, as well as a passive joint at the ankles. This model was followed by other versions of HAL. The most recent commercially available is version HAL-5, which offers improvement in the upper limbs of the exoskeleton (CYBERDYNE Inc., Japan). This modification enables an operator to lift loads that are up to 40 kg heavier than it is possible without HAL. The latest version of HAL-5 is intended for wearing on only one side of the body [2]. Unlike the first prototype, which had a passive ankle joint, in the latest version of HAL, the ankle dorsi-plantar flexion is driven also. Control is achieved by means of two cooperative systems: one triggers the activity of the actuators, and the other stores the operator's walking patterns in the memory. The functioning of the control system is based on data obtained from EMG sensors, GRF sensors, potentiometers, gyroscopes, and accelerometers.

Mori et al. presented a different assistive concept with a combination of active orthosis, mobile platforms, and telescopic crutches, called ABLE [3]. The transfer principle of its shoe-sized platforms is a crawler mechanism that can transport the operator not only on flat floors, but on uneven ground and outdoors as well. The platforms' upper layers are rotational, and thus allow the operator to turn. Orthoses are actuated at the hip and knee joints. To maintain balance, which is a key task of assistive devices, the telescopic crutches are equipped with an inclinometer. Through appropriate coordination of these parts, the patient is able to walk up/down stairs as well as stand up/sit down.

Researchers at Saga University (Japan) developed a robotic exoskeleton with 8 DoFs (four per leg) [11]. Its active joints reflect the hip and knee joints, where movement is actuated in the sagittal plane. The ankle joints are passive. A neuro-fuzzy controller receives EMG signals as well as signals from force sensors.

Another robotic system for special groups, such as the old and the disabled, is WPAL (Walking Power Assist Leg). WPAL has 6 DoFs per lower limb (three at the hips, one at the knees, one at the ankles, and one at the metatarso-phalangeal joint) [10]. In WPAL, only DoFs that are frequently used are actuated. In this case, it actuates only the hip joint and the knee joint to provide flexion/extension. Coupling between the operator and WPAL is provided by force sensors located on the thigh and in the soles of the feet.

A new approach to achieve portability of assistive robotic devices was demonstrated at Sogang University (Korea). Researchers there created EXPOS (EXoskeleton for Patients and Old by Sogang), which consists of two parts: lower limb exoskeletons and an active walker [15]. The active walker has a handle and moves on wheels, thereby providing support and maintaining the patient's balance. Taking out the batteries, motors, and control unit and placing them into the walker reduce the weight of the orthosis. Power is transmitted from the motor to the exoskeletons in wires. Along with the rotation of the motor, the wires also rotate, thus causing pulleys that are placed parallel to the joint connections to rotate as well. In this way, the motor's rotation leads to the movement of the exoskeleton. Each orthosis has a 1-DoF active joint at both the hips and the knees. Fuzzy control is produced on the basis of information from potentiometers and pressure sensors that sense the contraction of the thigh muscles. To allow the patient to comfortably sit/stand up, the handle height varies according to the angle of the knees.

Later, SUBAR (Sogang University's Biomedical Assistive Robot), an advanced version of EXPOS, was developed. SUBAR has an improved actuating power and a transmission mechanism for minimizing impedance, which enable it to provide more effective assistance [9]. A control algorithm inspired by aquatic therapy was introduced and implemented in SUBAR; this algorithm was experimentally verified [16]. The proposed method of therapy is now being prepared for clinical verification.

A second-generation IHMC [12] lower extremity robotic gait orthosis is called Mina. Mina has two actuated DoFs per leg, hip flexion/extension, and knee flexion/extension, for a total of four actuators. Mina does not provide hip ab-/adduction or medial/lateral rotation of the leg, and it employs a rigid ankle joint with a compliant carbon fiber footplate [17].

Argo Medical Technologies (Israel) unveiled the assistive exoskeleton ReWalk in 2008 [4]. ReWalk actuates the knee and hip flexion/extension. Patients must use crutches to maintain their balance. Sensors located on the chest determine the angle of the torso and measure the patient's shift in gravity and upper body movements. The use of this exoskeleton is limited to patients who meet certain height and weight criteria. Argo Medical Technologies (Israel) unveiled the assistive exoskeleton ReWalk [4]. ReWalk actuates the knee and hip flexion/extension. Patients must use crutches to maintain their balance. Sensors located on the chest determine the angle of the torso and measure the patient's shift in gravity and upper body movements. The use of this exoskeleton is limited to patients who meet certain height and weight

criteria. ReWalk$^{TM}$-I, which is intended for use in institutions, is currently commercially available for rehabilitation centers and hospitals in Europe and the USA.

Nine years of research (beginning in 2003) and development led to the construction of the exoskeleton Rex (Robotic EXoskeleton), which is manufactured by Rex Bionics (New Zealand). The company says that Rex is only truly suitable for manual wheelchair users who can self-transfer and operate hand controls [8]. In addition, Rex does not require any additional supportive aids such as crutches. A pair of robotic limbs controlled by a joystick allows sitting-to-standing, walking on level ground, and walking up/down stairs. Both Rex and Rehab Rex are currently available. The main difference between the two is the ability of Rehab Rex to be rapidly adjusted for multiple users who may vary in height, weight, and medical needs.

In 2010, Berkeley Bionics (USA) unveiled eLEGS, an assistive device that enables people with paralysis to stand up and walk [6,7]. eLEGS actively supports the knee and hip flexion/extension and is largely based on HULC. Hip abduction/adduction is loaded with a stiff elastic component to minimize the unnatural posture that the patient experiences, and the ankle is spring-loaded to reduce toe drop. The system uses a number of sensing modalities for control: pressure sensors under the soles, potentiometers, and an accelerometer/gyroscope board on the torso to measure the angle of the torso in the sagittal plane. The use of crutches is required with eLEGS. The device was tested on four paraplegic patients [6] and on three stroke survivors with chronic symptoms [7]. This device was developed specifically for use with paraplegics, though no studies have been published that characterize its performance or discuss its efficacy.

An exoskeleton powered by the control of the lower limbs for patients with spinal cord injuries was developed and tested [14] at Vanderbilt University (USA). This active orthosis provides active assistance in the sagittal plane at both the hips and knees. It is intended to be worn in conjunction with a standard AFO (ankle foot orthosis) that provides support at the ankle and prevents foot drop during the swinging of the legs. Joints are controlled by trajectory commands from a finite state machine that has twelve states, each of which is defined by a set of trajectories. The transitions between states are based on the position of the center of the mass projection on the ground plane. In this way, the operator is able to control the orthosis with his torso. In addition to walking, this orthosis also allows sitting and standing movements. In an experimental implementation, a paraplegic operator demonstrated the ability to walk within a set of parallel bars at an average speed of 0.8 km/h. Moreover, this exoskeleton provides repeatable knee and hip joint angles during walking, which reflect the joint trajectory shapes and amplitudes that characterize healthy walking [14].

For a summary and comparison device, as described above, see Table 1.

Laser range finders were added to each robotic leg of a lower limb exoskeleton (2 DoFs per leg: hip and knee flexion/extension) [13]. In addition to power-assistance, this exoskeleton provides fall prevention. The laser range finders that are attached near the exoskeleton's knee are able to scan and recognize the obstacles in the environment in front of the operator. When an obstacle or bump is detected, the exoskeleton tries to modify the user's motion trajectory to enable him/her to keep walking stably. sEMG is used to predict the user's motion and to provide power assistance. In addition, the sEMG joint angles are measured so the user can avoid obstructions. The capacity to ascend and descend stairs was also added [18].

The development of an active orthosis at a university in Brazil [19] is presently at a very early stage. Once developed, the system will be command-controlled (e.g., sit, stop, walk). The source of the commands can be buttons, a joystick, or voice. The first version that was realized allowed for hip and knee flexion/extension, and the commands were generated by a joystick.

A number of groups have published works on exoskeletal devices that have not yet progressed past the stage of preliminary investigations. These include MAPAS [20], the

**Table 1 – Full lower limb assistive devices – degrees of freedom, actuation and stage.**

| Device | Hip DoF | Knee DoF | Ankle DoF | Actuation | Status |
|---|---|---|---|---|---|
| HAL [1] | A-U-U | A | A-U-U | Motor | C |
| ReWalk [4] | A-U-U | A | U-U-U | Motor | C |
| eLegs [5–7] | A-U-U | A | U-U-U | Motor | C |
| Rex [8] | A-A-U | A | A-A-U | Motor | C |
| Mori et al. [3] | A-U-U | A | U-U-U | Motor | R |
| SUBAR [9] | A-U-U | A | U-U-U | Motor | R |
| WPAL [10] | A-U-U | A | U-U-U | Motor | R |
| Saga Univ. [11] | A-U-U | A | U-U-U | Motor | R |
| IHMC [12] | A-A-U | A | U-U-U | SEA | R |
| Hayashi and Kiguchi [13] | A-U-U | A | U-U-U | Motor | R |
| Vanderbilt Univ. [14] | A-U-U | A | – | Motor | R |
| Human | 3 rotations:<br>flexion/extension<br>ab/ad-duction<br>rotation | 1 rotation:<br>flexion/extension | 3 rotations:<br>plantar/dorsal flexion<br>in/e-version<br>pro/supi-nation | | |

*Note*: DoF: A, actuated; U, unactuated. Human movement: the ankle is a complex joint, where the axes of motion are not simply the three Euclidian axes. Stage: R, research stage; C, commercially available.

Rutgers HME [21], an exoskeleton by Hata and Hori [22], an exoskeleton by Acosta-Marques and Bradley [23] and W.W.H.-KH2 [24].

Although there are other robotic devices that provide walking assistance [25], they are not described in this section because they are not examples of exoskeletons.

### 2.2. Partial lower limbs exoskeletons

Honda has come out with a powered exoskeleton called Stride Management Assist [25], which actuates only the hips. This robotic device is intended for users who require a small degree of assistance in maintaining a functional gait speed, especially over longer distances.

One-joint active orthoses that runs parallel with the ankle, which are abbreviated as AAFO (Active Ankle-Foot Orthosis), are usually intended for persons with weakness in their ankle dorsiflexors.

An example of an AAFO is the orthosis developed at Yonsei University (Korea) [26], which was equipped with a rotary potentiometer and four force sensors. The sensors were used as ON/OFF switches connected to foot to detect gait events, and SEAs (Series Elastic Actuators) were activated on the basis of detected events. A preliminary study was conducted to show that the AAFO can prevent foot drop and toe drag [27].

Yoshizawa developed a powered ankle foot orthosis for the treatment of a ruptured Achilles tendon that enables the patient to walk forward with a fixed ankle [28]. The sole of this AAFO is equipped with a servomotor. The actuator can switch between the upright and the forward stepping posture of the patient. A weight support can be turned on a hinge by an actuator that is controlled manually by a hand switch. A prototype of a new version of AAFO has also been proposed [29], in which the conventional AFO is supported by a lower stand with a bearing at the ankle. The AFO can swing around on the bearing like a seesaw. A mechanical stopper and controlled friction at the ankle brake are used to prevent the user from falling backwards. A pressure sensor that is attached inside the shoe detects the beginning of the swing phase, and after a delay time, DC current is supplied to the brake.

The motivation behind the work of Fan and Jin was to develop a novel ankle exoskeleton to assist in the rehabilitation of physically weak persons [30]. The ankle is a complex joint for which it is difficult to design an exoskeleton, because it is limited to a small area. Their novel ankle exoskeleton with a 3-RPS (Revolute Prismatic Spherical) parallel mechanism operates in cooperation with signals from EMG sensors that are preprocessed by a neuro-fuzzy controller, which predicts the user's motion. This ankle exoskeleton can fully sustain the heavy load of a human body. A neuro-fuzzy controller that integrates an electromyographic (EMG) sensor was developed to realize real-time control of the ankle exoskeleton [31].

Analysis has shown that segmented foot models whose foot structure is close to that of the human body show better energetic efficiency and stability than models based on rigid-foot walking [32]. For this reason, a below-knee exoskeleton with a powered ankle and toe joints (EXO-PANTOE 1) was designed for patients with different ankle pathologies [32]. EXO-PANTOE 1 was adapted from the recently developed powered below-knee prosthesis PANTOE 1. Both joints are driven by two SEAs (Table 2), and the control circuit and the battery are worn in a small backpack.

**Table 2 – Partial assistive devices – development stage and clinical trails.**

| Device | Clinical trials | Weight (kg) | Status |
|---|---|---|---|
| Honda [25] | – | 2.8 | R |
| Yoshizawa [28] | [35] | 1.3 | R |
| Yoshizawa [29] | – | 2.2 | R |
| Fan and Jin [30] | [30] | Unpublished | R |
| EXO-PANTOE 1 [32] | [32] | 1.2 | R |
| Yonsei Univ. [26] | [27] | Unpublished | R |
| PPAFO [33] | [33] | 1.9 | R |

*Note*: Status: R, research stage.

A portable powered AFO (PPAFO) that provides untethered assistance for daily in-home rehabilitation treatment was developed at the University of Illinois (USA) [33]. Two force sensors in the PPAFO foot component were used to detect four separate gait events. The timing of the PPAFO assistance is dictated by these events to respond to different functional gait requirements. The rotary actuator is powered using a compressed $CO_2$ bottle that the subject wears on the waist.

A working group at Technical University in Berlin (Germany) proposed and constructed an exoskeleton that would support the thigh muscles during flexion and extension of the knee joint [34]. In their exoskeleton, a control system evaluates EMG signals that are sensed at the thigh muscles, the angle of the knee, and information from a force sensor. No ongoing work on this exoskeleton has been reported.

## 3. Rehabilitation exoskeletons

The aim of rehabilitative robotics is to facilitate the restoration of the patient's prior role and task performance after a neurological injury. Without robotics, training based on manual assistance is exhausting for the staff, and the duration of the training is thus limited by the fatigue of the therapist. Other drawbacks of the manual training are the lack of repeatability, and the fact that the patient's movement is evaluated only by observation. These multiple disadvantages can be overcome with the use of robotic rehabilitation devices. To be efficient, such devices need to be able to generate a precise and reproducible path. When this is achieved, the therapist's effort is reduced and the longer training sessions become possible.

The trend in the current research and design of rehabilitation exoskeletons is to develop a device that is capable of recognizing the patient's motor skills as well as their intentions, and is also able to provide feedback. These capabilities become possible when joints are equipped with sensors that provide information regarding angles, movement trajectories, and the monitoring of forces in action. Such devices are then able to assist the patient in performing his essential movements, and can also function effectively in providing of the therapy. Lee et al. carried out a survey that gathered information regarding gait rehabilitation devices from a clinician's point of view [36].

Three categories of the rehabilitative exoskeletons with controlled movement are described in the following subsections: stationary devices, full lower limb mobile (wheeled) devices, and partial mobile (wearable) devices. Passive systems and RGO (Reciprocating Gait Orthoses) with functional electrical stimulation are omitted.

### 3.1. *Stationary devices*

Frequently used rehabilitative tools include treadmill devices, which consist of a supportive framework and a robotic orthosis that exercises the patient in the required movements. In these devices, different design concepts use different support platforms, some of which are reviewed in this subsection. Descriptions of rehabilitation devices that attach the patient's legs to footplates, as is the case in end-effector-based systems (e.g., GaitTrainer, HapticWalker, LokoHelp and GaitMaster5) are not included owing to the absence of active exoskeletons.

An important element of the stationary lower limb rehabilitation devices is the mechanical framework that supports the patient. This supportive apparatus helps transfer the weight of the body, and therefore facilitates movement as well as ensuring safety and stability. Two basic types of supportive apparatus can be recognized: cBWS and sBWS [37]. In the cBWS (cable Body Weight Support) robotic system, the patient is put in a harness. In the sBWS (structural Body Weight Support) systems, support and stability are maintained by a robotic arm attached to the patient's back or waist. Both robotic systems are attached parallel to the lower limb segments and move in unison with the patient.

One of the key concerns for a robotic assisted gait rehabilitation device is the attainment of an optimal assistance technique. There are two main approaches to this goal. In the first approach, the patient is assisted only as needed, and only as much as is needed, so the patients are encouraged to make effort whenever they have the motor output to do so. In the second approach, the patient receives constant assistance, with the legs being guided on a fixed, rigid trajectory. Crespo et al. has reviewed several categories of assistance techniques for the robotic therapy devices [38].

The main objective of a study by Mehrholz et al. was to compare the effects of end-effector and exoskeleton devices that were used in electromechanical-assisted gait training following the patient's stroke, in a systematic review combined with the pooled analysis [39]. They found some evidence that electromechanical-assisted gait training combined with physiotherapy may improve the recovery of independent walking in such patients. They concluded, however, that it is still not clear if such devices should be applied in routine rehabilitation, or when and how often they should be used.

One of the stationary robotic devices that is commercially available is called Lokomat (Hocoma, Switzerland) [40]. It is a cBWS system in which movement is actuated in the sagittal plane at the hips and the knees. One DoF was added to allow vertical translation of the human body. The device uses force sensors to generate the actuator's control instructions. Lokomat provides adaptive control methods that minimize the forces interacting with the patient with respect to an adaptable reference pattern, thus controlling the entire gait cycle [40]. Other control algorithms have also been proposed [41,42]. Lokomat is the cBWS treadmill that has received the most extensive clinical evaluation [39,43–45].

Another commercial rehabilitative exoskeleton is AutoAmbulator (HealthSouth, USA, also known as ReoAmbulator) [46]. AutoAmbulator is a cBWS system that actuates movement in the sagittal plane at the hips and the knees by means of robotic arms that are strapped to the patients legs at the thigh and the ankle. The device is based upon a weight support system with a unique mechanical design that reduces its weight and overall dimensions, and also makes it quicker to put on and take off than the Lokomat. The device produces a symmetrical reciprocal gait by providing force throughout the entire gait cycle, including the swing phase.

Beginning in 2001, a team at the University of Twente (Netherlands) developed a robotic device LOPES (LOwer extremity Powered ExoSkeleton) [47]. In 2006, they built the first prototype, which had a total of eight actuated DoFs: two for horizontal pelvis translation, and three rotational joints per leg. Another DoF (for vertical motion of the pelvis) was left free to move unactuated within the design limits. The LOPES exoskeleton aims at support, not take over, those tasks that the patient is unable to perform without help, and does so by means of an impedance control scheme [48]. In 2010, LOPES became a part of the EU project Mindwalker, with the aim of proposing a test control algorithm that would make LOPES an autonomous exoskeleton.

A cBWS rehabilitative device with unilateral active orthoses, called ALEX (Active Leg EXoskeleton), was constructed at the University of Delaware (USA) [49]. ALEX is based on GBO (Gravity Balancing Orthosis) (developed at the same university). ALEX actuates hip flexion/extension and knee flexion/extension. The unilateral leg is designed to be used on the subject's right leg. In contrast with LOPES, ALEX does not use series elastic actuation for the backdrivability of the device, but rather, uses friction compensation. The mechanical structure and the control strategy were redesigned in the next version, ALEX-II [50], so that the unilateral leg can be used on the subject's right or left leg. This control strategy makes use of an assist-as-needed algorithm that provides less encumbered motion for its operators [51]. The device has been tested with two stroke survivors with chronic symptoms, and the results showed that the gait pattern of the patients had improved [52].

The summary and comparison of the described devices are stated in Table 3. There are other robotic devices that are in the early stages of research, namely ALTRACO and an exoskeleton developed at Zhejiang University.

Unlike most stationary rehabilitative devices, the sBWS exoskeleton developed by Beyl et al. [56] is designed to use an active ankle support. The development of this device and the active knee orthosis [57] is a part of the ALTRACO project (Automated Locomotion Training using an Actuated Compliant Robotic Orthosis), which operates under the umbrella of the University of Vrije in Brussels. The prototype is unilateral and has two pleated pneumatic muscles to provide the knee actuation.

The development of an exoskeleton at Zhejiang University (China) focused upon ergonomics [58]. Movement is provided by pneumatic muscles that are actuated and controlled by fuzzy and bang-bang algorithms. If the artificial muscle's piston is near a target position, a fuzzy control is applied. In the other case, in which, for example, the piston is in a distant position, the bang-bang algorithm is used. The mechanical

**Table 3 – Stationary rehabilitative devices – comparison of DoF, development stage and clinical trails.**

| Device | Hip DoF (flexion/extension-ab/ad-duction-rotation) | Knee DoF (flexion/extension) | Ankle DoF (plantar/dorsal flexion) | Clinical trials | Status |
|---|---|---|---|---|---|
| Lokomat | A-R-R | A | P | [39,43–45] | C |
| Auto-Ambulator | A-R-R | A | P | [53,54] | C |
| ALEX | A-R-R | A | P | [52] | R |
| LOPES | A-A-R | A | P | [55] | R |

*Note*: DoF: P, passive; A, actuated; R, rigid; Status: R, research stage; C, clinical usage.

construction of this exoskeleton produces hip and knee rotation in the sagittal plane (hip and knee flexion/extension).

### 3.2. *Full lower limb mobile devices*

Full lower limb mobile devices were developed to overcome a number of disadvantages of stationary devices and enable the patients to walk following a pattern that matches their requirements. Full lower limb mobile devices are often based upon a supportive framework with wheels.

WalkTrainer [59] consists of a cBWS system, a pelvic and lower limb orthosis, and a system of functional electrical stimulation. The pelvic orthosis has 6 DoFs and the user's active gait is controlled by an ankle joint. The lower limb orthosis contains sensors for the measurement of joint angles (hips, knees, ankles) and force sensors placed between the patient and the device for the measurement of their interactivity. Later, the orthoses were redesigned. A new proposal has 3 DoFs at the hip, 1 at the knee, and 3 at the ankle [60]. For practical reasons, in the construction of the prototype, only 1 DoF at the ankle joint was kept (in the sagittal plane). The functional tests and even the first clinical trials with paraplegics were undertaken [61].

NaTUre-gaits (Natural and Tunable rehabilitation gait system) was first constructed and assembled in 2006 at Nanyang Technological University (Singapore). This system is based upon four main functions for gait rehabilitation which are incorporated in NaTUre-gaits: the pelvic motion assistance, assistance for the lower limb, a cBWS system (with minimum restriction on the pelvic motion during walking), and functional over-ground walking [37]. The function of assistance of the lower limb is realized by robotic orthoses, which provide the actuated hip, knee and ankle movement.

There are also two rehabilitation systems that are in an early stage of research: a wearable robot being developed at the University Teknologi Malaysia, and a robotic system at the University of Bremen.

A single DoF wearable robot was designed at University Teknologi, to allow the patient to participate in repetitive movements and physical therapy [62]. It is an exoskeleton with a single motor located at the hip, and is designed in such a way that the knee joint motion follows the hip joint angle. It is also designed so that the hip angle is determined by the gear rotation, while the knee angle depends on the linkage. To meet the requirements for practicing dynamic balanced walking, a novel concept for a mobile robotic system has been proposed at the University of Bremen (Germany) [63]. Actuated DoFs were chosen such as in the Lokomat, i.e., one DoF in the hip and the knee for flexion/extension, and one to allow vertical translation. This system has been modeled and simulations have been performed.

Three other mobile rehabilitation devices have also been assembled; these are exoskeletons being developed at Tokyo Denki University [64], the University of Salford (UK) [65], and by the research team of Zabaleta et al. [66]. To the best of our knowledge, there is no ongoing work on these devices.

### 3.3. *Partial mobile devices*

The borderline between the rehabilitative and assistive partial lower limb robotic devices is not as clear as it is in the case of the full lower limb devices. In this regard, portability could be seen as an appropriate criterion for making a distinction. Thus, AFOs that have the potential to be realized as daily-wear devices are listed in Section 3.2, and AFOs intended strictly for in-lab rehabilitation are addressed in this section. Quasi-passive devices are also not included in this section, for while they may offer a solution to the problem of weight and partly address the issue of portability; also they lack the ability to provide supplemental assistive torque.

KAFO (Knee-Ankle-Foot Orthosis) was proposed and realized at the University of Michigan (USA) [67]. KAFO contained six artificial pneumatic muscles (an ankle dorsiflexor, an ankle plantar flexor, two knee extensors, and two knee flexors) with a proportional myoelectric control. Later, KAFO was used in a comparison of direct proportional EMG control and proportional EMG control with flexor inhibition produced by activation of the leg extensor muscle [68].

Recently, at the University of Alabama (USA), the preliminary research results for a fully mobile (i.e., untethered) powered KAFO were presented [69]. This orthosis provides the pneumatically actuated knee and ankle joints to assist the wearer's locomotion. The finite-state machine in the orthosis control system operates in four distinct states. The transitions between states are triggered by a certain set of conditions, which are often associated with highly definite events (such as heel strike) that can be easily detected using sensor signals.

The knee orthosis Tibion PK100 (previously known as PowerKnee) is a commercial product that was unveiled by Tibion Bionic Technologies (USA) [70]. Made of carbon fibers, the device is lightweight and portable. Tibion PK100 actively supplements muscle strength to enhance rehabilitation therapy and provide mobility assistance for patients with loss of muscle function. The device includes a control panel and a shoe with embedded force sensors. The control panel, which is placed on the thigh, contains a power source, LED display, and a speaker and buttons to operate the mode selection.

The ankle robot Anklebot is a robot that was developed at Massachusetts Institute of Technology (MIT) for rehabilitation

**Table 4 – Partial mobile rehabilitative devices – development stage, clinical trails and weight.**

| Device | Clinical trials | Weight (kg) | Status |
|---|---|---|---|
| Tibion PK100 [70] | – | Unpublished | C |
| Anklebot [71] | [72,73] | 3.6 | R |
| Pediatric Anklebot [74] | – | Unpublished | R |
| Univ. of Michigan KAFO [67] | [68] | 2.9 | R |
| Arizona State Univ. AAFO [76] | [83,84] | 1.75 | R |
| SUkorpion AR [75] | – | 5.35 | R |
| Univ. of Alabama [69] | – | Unpublished | R |
| Univ. of Delaware AAFO [78] | – | 2.5 | A |
| MIT AAFO [77] | [77] | 2.6 | A |
| Univ. of Michigan AAFO [82] | [85] | 1.7 | A |
| GAIT [79] | [79] | 2.71 | A |
| Nippon Bunri Univ. [80] | – | Unpublished | A |
| CIRRIS AAFO [81] | – | 1.7 | A |

*Note*: Status: R, research stage; C, commercially available; A, abandoned (there is no ongoing work more than 4 years).

of the ankle following a stroke [71], and was commercialized by Interactive Motion Technologies (USA). The robot provides independent, active assistance in 2 of 3 DoFs, namely dorsal/plantar flexion and inversion/eversion, and a passive DoF for internal/external rotation. Drop foot is typically addressed in the clinic via an ankle-foot orthosis (AFO) that restricts the ankle's range of motion. This approach, however, has limitations and offers little hope of reducing the impairment. To address the issue of impairment reduction, Anklebot was introduced to a clinic [72], where ten stroke survivors with chronic symptoms were tested with Anklebot by Khanna et al. [73]. In recent work, the development of a novel pediatric anklebot for children ages 5–8 was also reported [74].

A parallel mechanism-based ankle exoskeleton was presented by Sabancı University research team (Turkey) [75]. The robotic ankle, named SUkorpion AR (Sabanci University Kinetostatically Optimized Reconfigurable Parallel Interface on Ankle Rehabilitation), is reconfigurable. Reconfigurability is incorporated in the design such that a single device can be arranged as a 3UPS (Universal, Prismatic and Spherical joints; the prismatic is actuated) a manipulator to administer strengthening exercises, and as a 3RPS-R (Revolute, Prismatic, Spherical and Revolute joints; the prismatic is actuated) manipulator to support balance/proprioception exercises. Direct drive linear actuators are used in the prototype, and the use of series elastic actuators is envisioned for a later prototype. The weight of the device (5.35 kg) is distributed over the upper leg and the upper mid-calf by means of tight straps around the knee.

Robotic tendons (a DC motor in series with a custom-threaded lead screw and spring) were applied at Arizona State University to an AAFO (Active Ankle Foot Orthosis) [76]. Two robotic tendons were attached below the knee and to the tip of the toes; one on the left and one on the right side. By synchronous activation of the tendons, flexion/extension was achieved. Inversion/eversion was achieved by the activation of a single tendon.

Several ankle foot orthoses have been produced for which no ongoing work, to our knowledge, has been reported. These are the MIT AAFO [77], the University of Delaware AAFO [78], the GAIT exoskeleton [79], the Nippon Bunri University AAFO [80], and the CIRRIS AAFO [81], and AAFO at the University of Michigan in cooperation with the University of Washington [82]. The summary and comparison of partial mobile devices is stated in Table 4.

## 4. Challenges and conclusion

This paper has reviewed research in the field of lower limb exoskeletons and active orthoses. Despite much progress in the field of supportive robotic technologies, such as power sources, small and sensitive sensors, powerful computers, and lightweight materials, there is still a need to develop a lightweight exoskeleton that is compatible with the operator's minimal metabolic requirements. The key issue that must be addressed in wearable robotics is the high energy consumption of these devices as compared to their short battery lifetime. The benefits obtained from a solution to this problem would include portability, prolonged hours of operation, and accessibility for daily use.

Other problems posed by such human–machine systems are the optimal design of their anthropomorphic mechanisms and the effective control. The devices thus far developed are often unnatural in shape, noisy, and slow running. This problem can be solved by the development of better designed actuators and artificial muscles. Another significant aspect of the design of robots is that the exoskeletons are adapted to the human leg in terms of length, range of motion, and the number of degrees of freedom. These design elements can be accompanied by an increasing number of actuated DoFs, which leads to unnecessarily high power consumption and control complexity. Active and quasi-passive elements incorporated into a single robotic system might offer a promising solution to these issues. To develop a robotic system that fulfills the requirements of human movement, compromises must be made between the operator's (or therapist's) ideals and the technical feasibility of realizing these.

A high level of demand and expectation is placed on the robotic lower limb devices, such as natural movement, assist-as-needed capacity, adaptability, and safety. Preserving the dynamic stability of such systems is another great challenge. Maintaining the stability of assistive devices must often be provided by crutches or some type of walker, a solution that could be replaced by new approaches to effective gait models. Improved gait models should deal not only with the performance of ADL, but also with fall prevention and stumble recovery as well. Such a model could be generated by artificial intelligence. Artificial intelligence as such can lead to advances in gait modeling owing to the numerous advantages it offers, such as processing bulk of data with nonlinear relationships. The design of rapid and effective control algorithms is also necessary to prevent falling.

Presently, there is a lack of single full lower limb supportive robotic systems. The inability to control the movement of both lower limbs of a robotic system then leads to the crucial problem of ensuring stability.

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