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Research Article

A Review of Lower Limb Exoskeleton Assistive Devices for Sit-To-Stand and Gait Motion

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Abstract

This paper reviews several lower extremity wearable exoskeleton devices designed for people with various degrees of lower limb disabilities. Such devices provide an autonomous way to regain the ability to standup, sit down, and to walk. The goal of this work is to exhibit the different technologies used in devising exoskeletons up to date and to outline their features or their embedded techniques. Each exoskeleton system reviewed in this paper represents a technique that tackles issues associated with these devices such as comfort, ease of use, and compliance to its intended use. Eventually developers of exoskeletons offer users of such robotic systems a better life style.

Keywords: *Exoskeleton devices, Lower limb disabilities etc.*

1. Introduction

People with lower limb weakness or severe injury have a hard time moving without the support of an assistant. Helping these people to stand up and walk is a big task and puts the assistant under pressure, which may lead to falling and causing an injury to both the patient and the assistant. The most common locomotion tool used by people with lower limb disability is the wheelchair [Alberto Esquenazi *et al*, 2012]. Unfortunately, the limitations associated with the use of a wheelchair, from limbs locked in position and body constantly in a seated posture to environmental and spatial restrictions, are all reasons that can lead to health issues both physical and emotional to the wheelchair-bound person. One such issue is weakening the voluntary control of the trunk, which affects the seated posture and eventually increases pressure on the discs [S.n Kukke *et al*, 2004; Rachid Aissaoui *et al*, 2001]. A variety of tools have been devised to support the patient in performing the very basic and vital motions; stand up, sit down, and walk. These devices allow their users to overcome the difficulties associated with the motions. To perform such activities independently, these systems must be wearable robots that provide power, support, and balance due to the limited or lack of control over their lower limbs. Such assistive devices are called lower limb robotic exoskeleton devices, or simply lower limb exoskeletons.

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2. Exoskeleton

The literature is full of definitions for what an exoskeleton is. They vary from a simple definition to a very elaborate description. Merriam-Webster [Jetta Carol Culpepper, 2000] defines an exoskeleton as "an artificial external supporting structure." According to Pratt *et al*.[J.e. Pratt *et al*, 2004], an exoskeleton is "any device that a user can wear or drive". A definition I found very applicable and comprehensive [Larry Miller *et al*, 2016]: " Exoskeletons are prescription devices comprising an external, powered, motorized orthosis that are placed over a person's paralyzed or weakened limbs for facilitating standing, walking, climbing stairs, and performing activities of daily living." Therefore, it can be said that exoskeletons are external body strength amplifiers that boost or restore human performance.

Robotic exoskeletons constitute natural ways of exercising the body and the affected limb(s). They provide their users many benefits over traditional rehabilitation therapy. Here are some:

1) Exoskeletons provide safety ambulation in real-world settings that yield health benefits. [Larry Miller *et al*, 2016; Anneli Nilsson *et al*, 2014]
2) Exercising the affected limbs preserves muscle mass [J.D. Houle *et al*, 1999].
3) Restoration of sensory and muscle functions [K.J. Hutchinson *et al*, 2004; H.R. Sandrow-Feinberg *et al*, 2009].

4) Exoskeletons are feasible devices in improving walking abilities and balance. [Hiroaki Kawamoto *et al*, 2013]
5) The cardiorespiratory and metabolic demands of using an exoskeleton are equivalent to activities performed at a moderate intensity [Nicholas Evans *et al*, 2015], which constitutes a health benefit.
6) Exoskeletons speed up the rehabilitation period of the patient to gain body control and balance [Kengo Fujii *et al*, 2016].
7) The sense of independence, which elevates the quality of patient's life.
8) The Reduction of secondary health complications that may result if the patient is deprived mobility such as obesity, muscle atrophy and osteoporosis.

2.1 Exoskeletons by Application Type

The Exoskeleton industry is currently very active and steadily growing [Slavka Viteckova *et al*, 2013]. It constitutes an area of interest in the robotic field specially those oriented towards finding solutions for many medical issues. Although robotic exoskeletons find vast applications, we can group all of them under three types; assistive, rehabilitative, and empowering devices. Because the latter type, i.e. empowering devices, is meant for the abled bodied to allow them carry heavy loads in different terrains, this paper will focus in its review on lower extremity exoskeletons solely used as rehabilitative and as assistive (orthotic) devices.

2.1.1 *Rehabilitative Exoskeletons*

Rehabilitative exoskeletons are mainly used for the purpose of gait training therapy and are worn for a short period of time during the day. They help patients with spinal cord injuries (SCI) and other muscular or neurological injuries take the needed steps towards a full recovery of the lower part of the body. They can be stationary or mobile exoskeletons depending on the therapy needed. After the patient regains power of the affected limbs, there won't be a need for the exoskeleton. Therefore, rehabilitative exoskeletons are temporary devices and are adjustable to fit any patient.

2.1.2 *Assistive Exoskeletons*

Assistive (or orthotic) exoskeletons on the other hand, are manufactured for patients who lost the ability to regain power of their limbs. They are worn permanently inside and outside home as long as there's a need for locomotion. Assistive exoskeletons are mainly mobile robotic devices and are customized to fit the wearer.

3. Exoskeleton Design Considerations

Since exoskeletons are tied to body parts, they are divided into four groups: upper extremity, lower extremity, full body, and joint-specific exoskeletons [Joel C. Perry *et al*, 2007; Daniel Ferris *et al*, 2005; Marco Fontana *et al*, 2014; Jia-Fan Zhang *et al*, 2008]. Therefore, depending on the purpose of the wearable device, exoskeletons come in various structures. The body parts, the mechanical structure, the hardware embedded in the system, the control strategy, and the material of the embodiment are all factors that determine the overall structure.

Constructing an exoskeleton requires the use of a light material but at the same time one that would withstand large forces [Jeff Kerns *et al*, 2015]. In an ascending order in terms of material strength to weight ratio, the materials used in constructing exoskeletons are: Aluminum, fiber glass, carbon fiber, and carbon nanotube.

The hardware embedded in the system depends on the choice of actuators that are responsible for the motion of the exoskeleton plus the sensors that provide the system's feedback signal to guarantee safe and accurate trajectory. The job of the actuator is to convert the source of energy provided in the system into motion. The three main actuator types used in exoskeletons are electric, hydraulic, and pneumatic actuators [Juan C. Moreno *et al*, 2018]. Electric actuators are the more efficient yet heavier and louder than hydraulic and pneumatic actuators. A key element in the design of an exoskeleton is the use of sensors. There might be as many as 40 sensors in asingle exoskeleton. They are used to measure and monitor joint rotation, tilt, torque, pressure, as well as electromyogram (EMG) signals generated by muscle activities and neurological signals generated by the brain and the nervous system. The choice of the control system is critical in achieving the right motions. Several control systems are being applied in exoskeletons such as Serial elastic actuator (SEA), linear quadratic regulator (LQR), model predictive control (MPC), and proportional-integral-derivative (PID) among others [Jatsun Sergey *et al*, 2016; K. Kiguchi *et al*, 2004].

Table 1 lists manufacturers and businesses that currently produce lower limb exoskeletons in alphabetical order.

Current Research in Exoskeletons

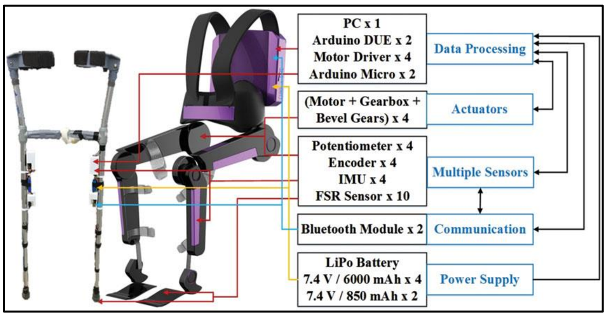
In the following sections, I will review a list of lower extremity exoskeletons and some of the recent research proposals of exoskeletons and control systems for the purpose of providing a comprehensive literature summary in the development of the topic in hand.

Table 1 List of Exoskeleton Manufacturers

AxoSuit	ExoAtlet	Honda	PhaseX AB	ROKI
B-Temia	Fourier Intelligence	Hyundai	Reha Technology	SUITX
Bama Teknoloji	Gogoa	Innophys	ReWalk Robotics	Technaid
Cyberdyne	GoXtudio	Marsi-bionics	Rex Bionics	Toyota
Ekso Bionics Holdings, Inc.	Hocoma	Parker Hannifin	Rotbot Systems	Walkbot

H2 Robotic Exoskeleton: This exoskeleton is made by Technaid in Spain for gait rehabilitation [Magdo Bortole *et al*, 2015]. There are six actuated joints in the robot placed in three areas on both legs: hip, knee, and ankle. DC brushless motors coupled with Harmonic Drive gearbox are incorporated in the actuators to reduce size and weight of the exoskeleton. Operation of the robot is managed by an assistive control algorithm that uses sensory information coming from 6 joint potentiometers, 18 Hall Effect sensors, 24 strain gauges and 4 foot switches to generate the right torque in order to complete the gait movement. The system is made out of Aluminum and weighs 12 Kg including the battery. One of the design advantages of H2 is that it is considered an open system that allows the integration of other systems. An example is a neural interface, which links the wearer's brain signals to the control algorithm of the robot, hence engaging the patient in operating the device.

Cuhk Exo Exoskeleton [Bing Chen *et al*, 2017]: This exoskeleton is developed by the Chinese University of Hong Kong (CHUK) as an assistive device targeting patients with lower extremity paralysis to perform sit-to-stand (STS) and gait motions. Both legs have a total of 7 degrees of freedoms (DOFs), with mechanical stops to ensure safety. Four of the seven DOFs are active (2 hips and 2 Knees), and three are passive (2 ankles and left hip external rotation). DC motors and planetary gearboxes made by Maxon are used as the actuators in all four active joints to generate the required torque. This system works with a pair of smart crutches to assist in the STS motion and to transfer almost half of the body weight to ground. The feedback system depends on multiple sensors; 4 potentiometers, 4 encoders, 4 inertial measurement units (IMUs), and 10 force sensitive resistances (FSRs). Data processing is done by a PC, two 84-MHz Arduino DUE microcontrollers, and two 16-MHz Arduino Micro microcontroller. Communication between the controllers, PC, and crutches is done by a Bluetooth module. The CUHK exoskeleton weighs 22 Kg and uses lithium polymer batteries that can run up to 3 hours.



EKSO GT Exoskeleton [Ekso Bionics, 2019; Exoskeleton Report, 2018]: This system is developed by Ekso Bionics, an American company, for the purpose of gait rehabilitation. It has a total of six DOFs (three on each leg). Only hip and knee joints are actuated, while the ankle joints are passive. The robot applies the smart Variable Assist (marketed as SmartAssist™) software, which engages the wearer in deciding the amount of robotic assistance needed during gait training. This feature broadens the types of patients that can benefit from this rehabilitation exoskeleton. The exoskeleton integrates several control walk modes including spotter, user, or other therapeutic activated modes.

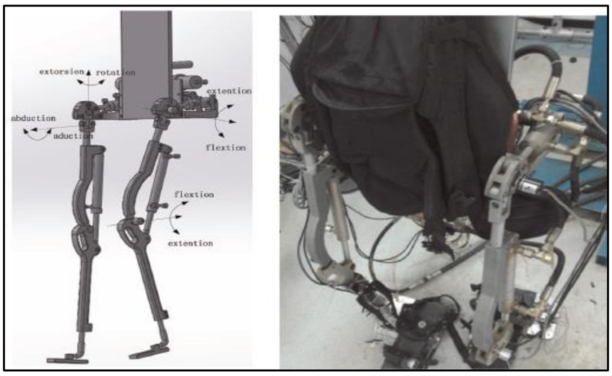
ANdROS: [Ozer Unluhisarcikli *et al*, 2015; Ozer Unluhisarcikli *et al*, 2011] This is an Active Knee Rehabilitation Orthoses System. It is suitable for patients with only one paralyzed leg for the purpose of gait rehabilitation and monitoring. It consists of two separate braces, one for each leg. One brace is actuated (active), and the other is passive (unactuated) with 2 hip DOFs. The exoskeleton works around monitoring the motion of the passive brace attached to the unimpaired leg by the help of built-in sensors. This type of rehabilitation is called active resisted, where the patient must move against a resistance; therefore it is intended for higher level patients. Each brace ends with an ankle-foot orthoses (AFO), which grounds the device and thus reducing the weight put on the user. In the sole of the AFOs are embedded switches to confirm the synchronization between the user and the machine as a feedback system. Other feedback signals derived from the device are load cell, high precision potentiometers, incremental encoders, rotary potentiometer, and a digital encoder to measure the shaft angle of the DC brushless motor.

A suggested embodiment of the system proposes the integration of a virtual reality system that can improve the results of the rehabilitation outcome.

Flexible Design Exoskeleton [Chunjie Chen *et al*, 2013]: Chen *et al*. developed a lower limb exoskeleton to assist patients with lower limb disability to walk. The design was based on a study of the movements of the human's lower limbs to determine the position and orientation of each joint during gait action. Three principles governed the design of the exoskeleton: 1) It should be isomorphic with human bone structure and movement. 2) The structure should be adjustable so it can fit different patient sizes. 3) Easy to wear and carry. 4) Lightweight, rigid, and safe. The device has 7 DOFs for each leg, 3 DOFs in the hip, 1 DOF in the knee, and 3 DOFs in the ankle. Active joints use Maxon brushed DC motors and the overall device weighs 28 Kg including the battery. The speed of the exoskeleton is slower than normal, 60 cm/S and the step length is 50 cm.

Jin *et al*. [Xinglai Jin *et al*, 2017]: developed an exoskeleton that will require less patient interaction force by improving the tracking performance of the robot. The design is based on two subsystems; one that would track the motion phase and the other would track the velocity of the motion. For that, the design incorporated a multi-sensor system in the sole to translate the intentions of the patient thus determining the motion phase. The multi-sensor system includes force-sensing resistors (FSR's) by Tekscan, and ribbon switches by AbleNet. Detecting the velocity of the motion, on the other hand, is achieved through the use of two 6-axis force sensors and an admittance model.

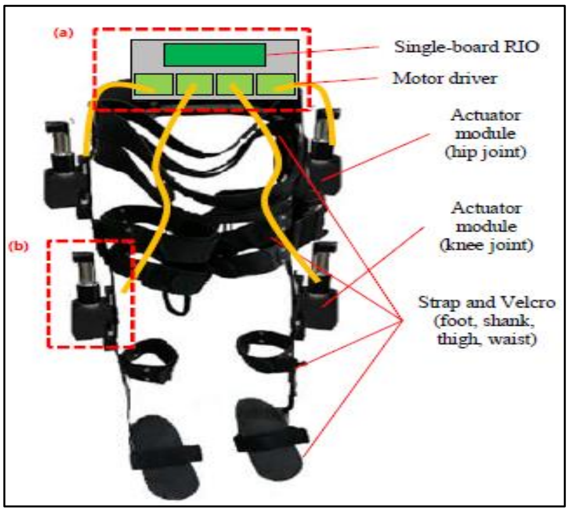
The exoskeleton structure is designed to have two powered anthropomorphic legs based on a pseudo-anthropomorphic architecture. It has a total of seven DOFs per leg; 3 hip DOFs, 1 knee DOF, and 3 ankle DOFs. The controller used in the exoskeleton is a combination of both a single-input fuzzy logic controller and an adaptive fuzzy sliding mode controller.



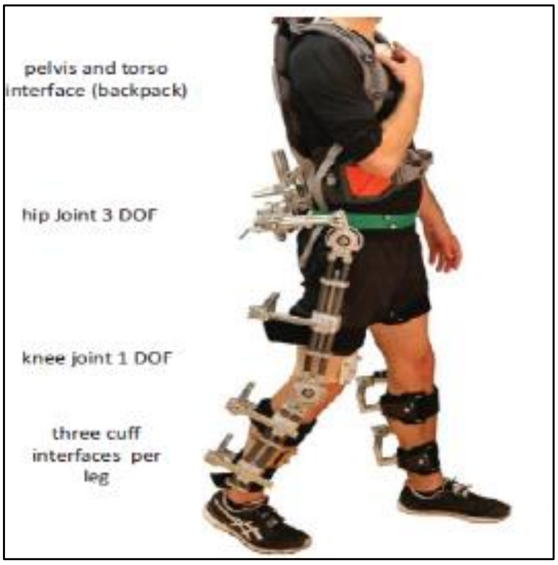
An exoskeleton robot for the rehabilitation of the lower limbs was developed by Gan *et al*.[Di Gan *et al*, 2016] The design focuses on giving the patient a great freedom of movement, convenience, and balance (safety). The structure of the device consists of three modules with 5 DOFs; the pelvic module (1 DOF), the thighs module (2 DOFs), and the legs module (2 DOFs). The thigh and torso modules can be adjusted in length to accommodate different patients. The thigh torso module is actuated using a Maxon flat motor with a Harmonic Drive gearbox having a 160:1 ratio, whereas the sensory system consists of an inertia measurement unit. The system weighs approximately 11.6 Kg, which is relatively low.

Lokomat Exoskeleton [R. Riener *et al* 2010]: It is a computer controlled therapeutic exoskeleton for gait training with a body weight support commercially available by Hocoma AG in Switzerland. The patient is strapped to the orthoses at the waist, the thighs, and at the shanks. Both hip and knee joints are actuated joints with the ankle movements are passively supported. Angular position of the legs plus the torques at the active joints are measured by potentiometers and force sensors, respectively. Compliance of the rehabilitation robot is managed by a path controller, which proved better therapeutical results than previously used impedance controller.

Kim *et al*. [Suin Kim *et al* 2014] designed an exoskeleton that will respond to the wearer's intentions and provide the required assistance instead of restraining the patient's motions. This was achieved using a pure force mode control. To implement such a control mode in the human-robot interaction system, four actuated joints are used in the hip and knee. The mechanism applied in this system is the series elastic actuator (SEA). Each actuator module is made of a brushless Dc motor and a torsional spring. The exoskeleton frame is tied to the patient through Velco straps at the waist, hips, shanks, and feet.



Bartenbach *et al*. [Volker Bartenbach *et al*, 2015] developed a rehabilitation exoskeleton model with some flexibility to improve the human-robot interaction. The mechanical structure of the exoskeleton had to be as lightweight as possible (10 Kg) with smooth-running joints (8 DOFs). To reduce the constraint associated with misalignment, the design incorporates misalignment compensation joints (6 DOFs). The system uses 20 different sensors to measure alteration in gait kinematics, human-robot interaction forces, movements of the joints, perceived comfort, and physical load.



Karthikeyan P *et al*. [P. Karthikeyan *et al*, 2016] designed a modular exoskeleton for the geriatric people to assist them in their walking. The design is simple thus reducing the cost of the device. It transfers the weight of the robot to ground so the patient doesn't bear additional weight. Each leg is powered by two actuators with 4 sensors that sense how much power is needed to support the leg. Two rotary motors are in the knee and ankle joints, and the four pressure sensors are embedded in the thigh (1 sensor), the shank (1 sensor), and the foot modules (2 sensors). The device applies safety algorithm to protect the patient from falling or from undesired action by the robot.

Meng *et al*. [Liang Meng *et al*, 2012] worked on a design that would optimize the sensors in the exoskeleton to provide a lighter weight, smaller size, lower power consuming, and wearable sensors. Therefore, the design is based on the use of fiber-optic sensors manufactured by Measurand that prove advantageous over EMG sensors. The controller design is based on a 7 lower limb DOFs (3 hip DOFs, 1 knee DOF, and 3 ankle-foot DOFs). All six robot joints are hydraulically actuated with control valves. The system can recognize six body postures: still, walking, running, squatting, standing, and on slope.

Sanngoen *et al*. [Wanayuth Sanngoen *et al*, 2017] developed a low cost easy to use lower limb exoskeleton. The device is called Walking Assist Robot (WAR) and is made for rehabilitation purposes. There are four control functions this device can provide: step walking, sitting down, standing up, and emergency function. It has four DOFs with actuated joints at the hips and knees. The distributed control system technique is used in this robot with one master controller and four slave microcontroller. The body of the device is made of Aluminum and weighs 25 Kg and can host patients up to 80 Kg in weight and 180 cm long.

HAL : The hybrid assistive limb (HAL) exoskeleton is both an assistive and an augmentative device manufactured by Cyberdyne Inc. The robot is controlled by two systems: "Cybernic Voluntary Control System" and "Cybernic Autonomous Control System" [Yoshiyuki Sankai *et al*, 2010]. These two complementary control systems guarantee operation for different types of wearers; from completely paralyzed to a fully healthy well-being. The exoskeleton supports STS, gait, and up/down climbing motions. HAL has the ability to understand the intentions of the wearer by using the bio-electric signals (BES) generated by the body to guide the robot. It uses DC motors to run the actuators with three types of sensors: ground contact sensors, joint angle sensors, and bioelectric sensors [HEXA-ROBOTS, 2019; CYBERDYNE, 2019]. The HAL exoskeleton for medical purposes has 3 DOFs, uses lithium-ion battery, and weighs 12 Kg.

Conclusion

A review of several wearable robotic exoskeletons has been carried out in this paper. The review was based on the available commercial and research exoskeleton devices at the current market and academia, which have been proven with several successful trials and uses. Assistive and rehabilitative exoskeleton suits were presented with highlights on the strength points of each type of the available exoskeletons. The review provides a brief and focused insight of robotic assistive technology researchers who are willing to contribute to the field of exoskeletons. The industry of lower limb exoskeleton is still long ways from reaching the ultimate version that will provide a natural locomotion means for paralyzed people. There are still ways to improve in the trajectory of the exoskeleton and make it follow the intended motion of the wearer's brain using various advanced control techniques and optimization methods. There are also a need to improve the size, weight, and shape of the exoskeleton embodiment to make it almost transparent and hence feels like a natural leg. The raise of soft robotic suits issue is a promising step towards achieving affordable, lightweight and comfortable exoskeletons.

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