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A Review of Lower Limb Exoskeletons

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Abstract
In general, exoskeletons are defined as wearable robotic mechanisms for providing mobility. In the last six decades, many research work have been achieved to enhance the performance of exoskeletons thus developing them to nearly commercialized products. In this paper, a review is made for the lower limb exoskeleton concerning history, classification, selection and development, also a discussion for the most important aspects of comparison between different designs is presented. Further, some concluding remarks are withdrawn which could be useful for future work.
Keywords: Exoskeletons, Lower extremity exoskeleton, Wearable robots

1. Introduction

There still are many challenges associated with exoskeletol and orthotic designs that have yet to be perfected, the advances in the field have been truly impressive [1]. Heavy objects are typically transported by wheeled vehicles. However, many environments, such as rocky slopes and staircases, pose significant challenges to wheeled vehicles. Within these settings, legged locomotion becomes an attractive method of transportation, since legs can adapt to a wide range of extreme terrains [2]. Also, there are numerous causes that can affect the functioning of the human locomotor system, leading to the appearance of joint disorders in the lower limb and generating atypical gait patterns. The importance of research and development in assistive technologies to compensate pathological gait have been recognized since the beginning of the twentieth century and numerous challenges still lie ahead to make their clinical application a reality [3]. So the exoskeleton is an electromechanical device that is worn by a human operator and designed to increase the physical performance of the wearer. This performance increase might include increased load carrying capacity, lower metabolic expenditure, or running at faster speeds or for longer distances, Because of the close interaction between the wearer and the exoskeleton, these devices must be mechanically compatible with human anatomy, able to safely move in concert with the wearer without obstructing or resisting movement [4].

In order to be useful and accepted by people, these exoskeletons must achieve certain capabilities and performance characteristics including the following:

1) Human Performance Enhancement: The exoskeleton should increase wearer’s strength, endurance and/or speed enabling them to perform tasks that they previously could not perform.
2) Low Impedance: The exoskeleton should not impede the user’s natural motion.
3) Natural Interface: The exoskeleton should provide a natural, intuitive, transparent interface such that the user feels as if the exoskeleton is a true extension of his/her body rather than something that the user is driving.
4) Long Life: The exoskeleton should have sufficient duration of use between energy system recharge and a quick and easy recharging method.
5) Comfortable: The exoskeleton should be comfortable and safe to wear and easy to on and off [5].

Robotic exoskeletons can be used in rehabilitation to retrain the nervous system to walk, enhance the abilities of healthy individuals such as the worker in aircraft or fireman, and/or help the disabled to live more independently [6].

A lower extremity exoskeleton is a mobile machine worn by a person that supplies at least part of the activation- energy for limb movement. It combines human intelligence and machine power, such that it enhances the intelligence of the machine and the power of the human operator. As a result, the human operator can achieve what he would not otherwise be capable of by himself [7].

In the mechanical design of the exoskeleton, different design criteria should be considered. The design criteria as outlined by researchers at the Selcuk University [8], includes (1) Ergonomic and comfortable design (2) high maneuverability (3) lightweight and strong structure (4) adaptability to different users and (5) user safety.

2. Historical Background

The idea of using exoskeletons to augment human locomotory performance dates back to 1890 when Nicholas Yagn conceptualized an apparatus for facilitating walking, running, and jumping figure 1 (a). His device consisted of a large bow spring that was interconnected between a hip belt and a foot attachment. The bow spring stores energy developed by the weight of the body and by the act of walking, running, or jumping. The Yagn's bow spring design lacked a degree of freedom at the knee. Therefore, to achieve steady state running the user would hop from one leg to the other. Bending of the knee for normal walking and running would require storing prohibitive amounts of energy in the bow spring. The Yagn's apparatus was completely passive and human powered [12], [21].

In the late 1960s, General Electric Research (Schenectady, NY), in cooperation with researchers at Cornell University and with financial support from the U.S. Office of Naval Research, constructed a full-body powered exoskeleton prototype. "Hardiman" (from the "Human Augmentation Research and Development Investigation") figure 1 (b), the exoskeleton, was an enormous hydraulically powered machine (680 kg, 30 DOFs), including components for amplifying the strength of the arms (including hands but without wrists) and legs of the wearer [1].

In comparison to many other augmenting exoskeletons, the intention of the Hardiman project was to drastically increase the strength capabilities of the wearer (approximately 25:1). A patent filed in 1966 describes what was presumably the initial Hardiman concept, and was much sleeker and more compact than what was eventually constructed [22].

In 1969, the kinematic walker was developed figure 1 (c). Each leg of the kinematic walke' consisted of 2 degrees of freedom with an active joint at the hip and a passive joint at the ankle. The knee was locked straight and the hips were actuated via pneumatic pistons mounted on the waist. The resulting gait was of the sliding foot type [23].

(a) (b) (c) (d) (e)

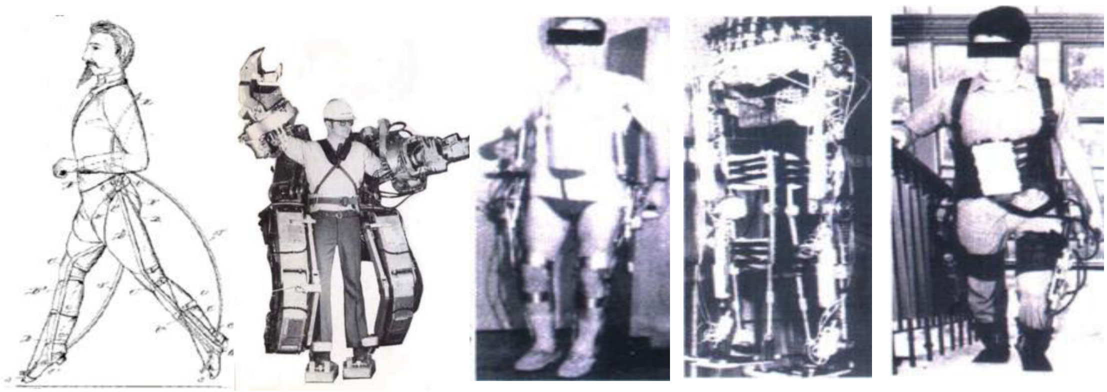

Fig .1.
(a) Represent the Yagn design (b) Hardiman design (c) The Kinematics walker design (d) Partial design (e) The Active suit

In 1970, the first active exoskeleton with 3 degrees of freedom per leg was developed. This exoskeleton, known as the 'partial exoskeleton' figure 1 (d), introduced a degree of freedom at the knee. It employed 7 pneumatic actuators and 14 electromagnetic solenoid valves.

The exoskeleton enabled a paraplegic to walk, but was unable to provide dynamic stability. A rolling aid such was needed to prevent the participant from falling sideways. Both the 'kinematic walker' and the 'partial exoskeleton' had an air compressor off the board [23].

In 1978, the 'active suit' was developed figure 1 (e). The 'active suit' was a self-contained, microcomputer controlled active exoskeleton powered by servo electric drives. A 100W servo electric drive was employed for the hip joint, and a 50W servo electric drive coupled to a worm-gear reducer was implemented for the knee joint. The system was controlled by a chest-mounted microprocessor control system and powered by nickel-cadmium batteries. The exoskeleton corset was manufactured using strong felt and light alloy stiffeners. The exoskeleton was tested by a patient with muscular dystrophy. The patient was able to adapt to the suit quickly and use it without difficulty [24].

In 1991, the 'Spring Walker' was developed as a passive exoskeleton for running figure 2 (a), The 'Spring Walker' was a complex, human powered, kinematic exoskeleton. The exoskeleton consisted of a kinematic linkage whose joints incorporated springs. The legs of the 'Spring Walker' were in series to the human, such that the human feet do not touch the ground. Although very complex, the 'Spring Walker' allowed the human to achieve a moderate running pace [25].

In 2002, Tsukuba University in Japan developed an exoskeleton called the 'Hybrid Assistive Leg' (HAL-3)figure 2 (b). The exoskeleton employed harmonic drive motors at the hip, knee, and ankle joints. Power for the motors was supplied by a battery pack mounted on the backpack. The control strategy was to estimate the human's joint torques and use a feed forward algorithm to command torques to the motors. The human joint torques were estimated by measuring the foot's ground reaction force and activation level of the leg muscles. Muscle activation was achieved by measuring the myoelectricity (EMG) signals on the surface of the skin. The ground reaction force was measured using a load cell embedded beneath the exoskeleton foot. This exoskeleton faced a problem, where the EMG based control strategy was not fully solved, and the wearer experienced discomforts due to controller errors. The exoskeleton's mass was 17kg [26]. The Hybrid Assistive Limb (HAL) was developed by the University of Tsukuba in Tsukuba, Japan for several appli- cations such as helping healthy people to enhance their strength and assisting people with mobility disorders to perform essential daily life motions [63] [64]. The HAL systems have different configurations such as a full body version, a two-leg version, and a single leg version. The fifth version of HAL (HAL-5) is a full body exoskeleton designed for augmenting the strength of able-bodied per- sons and for rehabilitation [65]. The HAL-5 weighs w23 kg with 15 kg worn on the lower body. The HAL-5 has eight controllable joints, which include the lower limb joints and upper limb joints, and is actuated by electric motors. It allows workers to carry heavier loads and function as an aid in emergency rescue. The HAL-5 can help a person to hold and lift heavy objects weighing up to 70 kg.

In 2004, the 'Berkeley Lower Extremity Exoskeleton' (BLEEX) used linear hydraulic actuators to power the hip, knee, and ankle in the sagittal plane figure 1(c). The exoskeleton is powered by an internal combustion engine which is located in the backpack. The hybrid engine delivered hydraulic power for locomotion and electrical power for the electronics. The exoskeleton interfaced to the human by means of a vest, waist belt, and boots that clip into snowboard bindings. The control strategy allowed the human to provide the intelligent control while the actuators provided the necessary strength for locomotion. The complex control algorithm was implemented using only measurements from the exoskeleton and not from the human or the human-machine interface. The Berkeley exoskeleton was able to carry a load 751b at a walking speed of 1.3m/s [25] [27].power for locomotion and electrical power for the electronics. The exoskeleton interfaced to the human by means of a vest, waist belt, and boots that clip into snowboard bindings. The control strategy allowed the human to provide the intelligent control while the actuators provided the necessary strength for locomotion. The complex control algorithm was implemented using only measurements from the exoskeleton and not from the human or the human-machine interface. The Berkeley exoskeleton was able to carry a load 751b at a walking speed of 1.3m/s [25] [27].

In 2004, Sarcos of Salt Lake City, Utah, created an exoskeleton similar to that of Berkeley figure 2 (d). Rotary hydraulic actuators were located at the hip and knee with a linear hydraulic actuator for the ankle. The Sarcos' control algorithm is similar to that of Berkeley's where the exoskeleton senses what the user's intent is and assists in performing the task. Twenty sensors on each leg are processed by an onboard computer to deliver what Sarcos dubbed, 'Get out of the way control'. Sarcos also has a portable internal combustion engine to deliver the hydraulic power necessary for locomotion. The Sarcos exoskeleton is able to carry a 90kg payload [28].

(a) (b) (c) (d) (e)

Fig.2.

(a) Spring walker (b) Hal 3 (c) BLEEX (d) Sarcos exoskeleton (e) Robo knee exoskeleton.

In 2004 the Robo knee is made figure 2 (e), it is a one degree of freedom exoskeleton, which achieves a high level of transparency User intent is determined through the knee joint angle and ground reaction forces Torque is applied across the knee in order to allow the user’s quadriceps muscles to relax. Low impedance is achieved through the use of Series Elastic Actuators. The RoboKnee allows the wearer to climb stairs and perform deep knee bends while carrying a significant load in a backpack. The device provides most of the energy required to work against gravity while the user stays in control, deciding when and where to walk, as well as providing balance and control [5].

In 2006 a gravity balancing lower extremity exoskeleton was designed figure 3 (a), it is a simple mechanical device composed of rigid links, joints and springs, which is adjustable to the geometry and the inertia of the leg of a human subject wearing it. This passive exoskeleton does not use any motors or controllers, yet can still unload the human leg joints of the gravity load over the full range of motion of the leg [29].

In 2006 Sogang University developed a tendon-driven exoskeleton system EXPOS (exoskeleton for patients and the old by the Sogang University) [31]. This device integrated an automatic platform as a caster walker to retain the balance during the rehabilitation process. The handlebar on the platform is pneumatically actuated to synchronize with the up-down motion of the user during walking. The exoskeleton, which has powered hip and knee joints for both lower limbs, has force transmission through tendons and pulleys. The transmission is placed on the walker to reduce the moving mass on the exoskeleton. Another prominent property of EXPOS design is the usage of air bladders, whereby the pressure sensors are implemented on thigh and in shoes. The purpose of the pressure sensor is to detect human intention and muscle movements. To distinguish the design of EXPOS with the rest of exoskeleton design, the air bladder is tightly wrapped around the key muscles in the legs so that the air pressure varies during muscle contraction. Recently, a newer version of EXPOS was proposed, whereby the name was altered to SUBAR (Sogang University biomedical assistive robot) [32]. SUBAR follows the same concept as EXPOS, but with an increment in output torque (from 7 NM to 44.0 NM) and reduction of weight (from 3.2 kg to 11.0 kg). Thus, an impedance compensation algorithm was implemented to reduce the resistive force.

In 2007 treadmill-based exoskeleton is ALEX (active leg exoskeleton)figure 3(b), which is designed in University of Delaware. It is developed on the basis of a passive Gravity Balancing Orthosis (GBO). ALEX possesses four DOFs in pelvic motion and two active DOFs on the exoskeleton for hip and knee joints, which are actuated by linear actuators. Force-torque sensors are integrated to measure the interaction force between the exoskeleton and user's limbs [33] [34].

In 2011 Nanyang Technological University (NTU) has introduced an over ground walking rehabilitation device known as NaTUre-gaits (Natural and TUnable rehabilitation gait system). The device consists of an exoskeleton with actuated hip-knee-ankle joints, BWS system and a mobile platform [35]. One of the remarkable features of this device is that the system provides five actuated DOFs on pelvic to assist in the pelvic movements. The advantage of this additional feature is to promote motor recovery via repetition of therapy. In spite of the said features in which the mobility of the patient is improved, these actuators, however, make the system relatively complicated and cumbersome [36].

In 2011, a modified version of ALEX II was proposed in which the rotary motors are applied to actuate the hip and knee joints directly instead of linear actuators. With the rotary motors, the joints achieve larger ranges of motion which will further enhance the treatment. ALEX, which has been tested on both healthy and stroke subjects, has joints on one leg only [37] [38] [39].

In 2008 an energetic-autonomous powered knee exoskeleton to facilitate running is manufactured and tested (Yobotics, Inc., Cincinnati, OH, USA), The device consists of a knee brace in which a motorized mechanism actively places and removes a spring in parallel with the knee joint. This mechanism is controlled such that the spring is in parallel with the knee joint from approximately heel-strike to toe-off, and removes from this state during the swing phase of running [40].

In 2009 Walk Trainer, which is a commercially available over ground mobile device figure 3 (c), was developed by the Laboratoire des Systemes Robotiques (LSRO) at the EPFL (Ecole Polytechnique Federale de Lausanne, Figure 11) [41]. It comprises a mobile frame that can follow the user during exercise. On the frame, there is a BWS system that exerts lifting force to prevent the user from falling. This device has a motion guide to pelvic with six actuated DOFs. A force sensor is implemented to monitor the interaction force between robot and user. The exoskeleton, on the other hand, is powered by linear actuators through crank mechanisms. In addition, a twenty-channel real time muscle stimulator is implemented to stimulate the muscles for cycling, rowing and walking activities.

In 2009 it could build and tested lightweight carbon-fiber ankle-foot orthoses (AFO) with artificial pneumatic muscles capable of powering both ankle plantar flexion and dorsiflexion during human walking. They concentrated our initial efforts on the ankle because it plays a crucial functional role during normal walking figure 3 (d). Then they designed the (KAFO) figure 3 (e), a unilateral powered knee-ankle-foot orthosis (KAFO) with antagonistic pairs of artificial pneumatic muscles at both the ankle (i.e. Plantar flexor and dorsiflexor) and the knee (i.e. Extensors and flexors). The orthosis pneumatic muscles were controlled using surface electromyography recordings from the user's own biological muscles (i.e. Proportional myoelectric control) [42], [43].

(a) (b) (c) (d) (e)

Fig.3.
(a) Gravity balancing exoskeleton (b) ALEX exoskeleton (c) WALK TRAINER (d) AFO exoskeleton (e) KAFO exoskeleton.

In 2010 a stationary 1-DOF exoskeleton designed and built for assisting knee flexion and extension exercises figure 4 (a). The aim was to use the pendular motion of the leg's shank as a scaled-down model of the swing motion of the entire leg when walking, and to investigate the effects of an active exoskeleton dynamics on the kinematics and energetics of leg-swing motion [44].

Also in 2010 the Moon Walker was made figure 4(b) , it is a lower limb exoskeleton able to sustain part of a user's body weight. This exoskeleton can be used for rehabilitation, to help people having weak legs, or to help those suffering from a broken leg, to walk. It can also be used as an assistive device helping people carrying heavy loads. Its main characteristic is that a passive force balancer provides the force to sustain body weight. An actuator is also required, but is used only to shift that force the same side as the leg in stance. Consequently, MoonWalker requires very low energy to work on flat terrains. The motor can provide part of the energy to climb stairs or slopes. This approach can help improving the energetic autonomy of lower limb exoskeletons [45].

In 2012 A research group from University of Auckland, New Zealand, proposed a robotic orthosis powered by pneumatic artificial muscle actuators [46]. This system is composed of an exoskeleton for one leg only. PAM differs from SEA in working principles, but has the compliance characteristics due to the fact that air is compressible. This orthosis has a BWS frame with two DOFs on the waist namely lateral and vertical translations; while hip, knee rotations are actuated in the sagittal plane. A single PAM can provide peak joint torque of 50Nm, which is sufficient for rehabilitation. Impedance control was implemented with pneumatic muscle actuator. However, due to the high nonlinearity effect of the pneumatic system, modeling and control become foremost concerned in influencing the performance of the exoskeleton [47].

Also in 2012 ReWalk is a device designed to treat individuals with SCI problems, especially the patients with total thoracic or low level motor function in walking [48]. The ReWalk has motorized hip and knee joints for both legs. Also, battery and controller set are integrated in a backpack, besides the necessity of using the crutches in retaining the balance while walking. In addition, there is a wireless pad controller on the wrist that is able to command and instruct the exoskeleton to perform transition movements such as from standing to sitting or likewise, stairs climbing or normal walking postures.

In 2013 a Walking Assistance Lower Limb Exoskeleton for Paraplegic Patients that can measure the center of pressure was present figure 4 (c), this exoskeleton is made to assist paraplegic patients who cannot move their legs, the exoskeleton helps the motion generation of the lower limbs of the wearer. In order to minimize discomfort for the wearer, the lower limb exoskeleton is designed with 3 degrees of freedom

3(DOF) of the hip joint, 1DOF of the knee joint and 3DOF of the ankle joint, making 7 DOF in a leg. Among these 7 DOF joints in a leg, two joints - the hip and knee joints are activated in the sagittal plane. Electric motors are used as actuators due to their higher efficiency and lower weight [49].

In 2013 Another remarkable exoskeleton in treating the neurologically impaired patients is Ekso (Exoskeleton Lower Extremity Gait System) which was originally named as eLEGS [50] figure 4 (d). This design has been developed by Ekso Bionics. Ekso is powered by hydraulic actuators, with a hydro-cylinder and battery integrated on a backpack. Ekso is suitable for user less than 220 pounds, and it is adjustable to fit user whose height is ranging from 5ft 2in to 6ft 4in. Ekso provides transition motions such as sit-to-stand, stand-to-sit and walking postures. In the later version of Ekso, control of the movements via buttons has been introduced in which three modes of the transition movements can be selected. The first mode is the initial step in allowing the therapist to initiate the patient's step. The user progresses from the sitting position to standing position. The patient subsequently continues to walking position with the assistance of crutches in which this is often treated as their first session. The second mode is the Active Step whereby the patient takes the control to actuate their steps via buttons on the crutches or walker. As for the third step, which is known as the Pro Step, the patient achieves the successive step by moving their hips forward and shifting them laterally (from side-to-side) [50].

In 2013 indego, a well-known over ground exoskeleton, has been developed by Vanderbilt University figure 4 (e). The said exoskeleton, which has been commercialized by Parker Hannifin Corp, is used to treat paraplegic individuals. Due to its compact and modular design, the 27 lbs Indego allows patients to wear this device while sitting in a wheelchair. The design of this exoskeleton consists of actuated hip and knee joints for both legs. Moreover, additional forearm crutches are needed to maintain the balance of the patient [51]. The system is different from the active orthosis as the actuation system for this robot exoskeleton obeys the principle of the power dissipation braking system at hip and knee joints. The gait is induced by functional electrical stimulation (FES), controlled by the locking and releasing of the brakes [52].

(a) (b) (c) (d) (e)

Fig .4.

(a)1 dof exoskeleton (b) moon walker exoskeleton (c) Walking Assistance Lower Limb Exoskeleton for Paraplegic Patient (d) EKSO exoskeleton (e) Indego exoskeleton.

In 2013 a treadmill-based exoskeleton called the MINDWALKER [53], is proposed figure 5 (a). This thought controller exoskeleton, which is displayed in, is a device developed for SCI patients in allowing them to recover the walking abilities besides improving the normal social life in today's society. In this system, the brain provides the control of the supporting exoskeleton by excitation signals from the brain, which will able to provide kinematics for controlling the exoskeleton. In this exoskeleton, steady state visually evoked potential modality of control based on visual simulinks. With this intention based control exoskeleton, the blinking state of LEDs at four different frequencies are used to indicate the intention of the patient in initiating, terminating, halting and walking faster or slower pace. The lower body mobility control lies in the extraction of signal from the muscles. By extracting the signals from the shoulder when the subjects are walking on the treadmill, the movement' signals are processed to control the kinematics lower limb of the exoskeleton.

In 2013 an innovative lower extremity exoskeleton, SJTU-EX, is demonstrated at Shanghai JiaoTong University figure 5 (b), which mainly aims to help soldiers and workers to support a payload in motion. Each pseudo-anthropomorphic leg of SJTU-EX has four active joints and two passive joints, and the joint ranges. We are optimized in consideration of both safety factors and the realization of typical motions. Springs were applied in the leg to eliminate the effect of gravity. The results of dynamic simulations were used to determine the actuated joints and the passive joints. Novel Hy-Mo actuators are introduced for SJTU-EX and the layout of the actuator for Diamond Side 2 is described in detail as a design example [7].

In 2015 an ankle exoskeleton is designed with the goal of assisting the human user and reducing overall energy costs figure 5 (c). Putting an ankle exoskeleton on the leg, however, automatically incurs a metabolic energy penalty because it adds distal mass. Reducing total device mass helps minimize this incurred penalty. Ankle exoskeletons also interfere with natural movements and, although this problem can partially be addressed with good control, some interference is unavoidable due to the physical structure of the device [54].

(a) (b) (c)

Fig .5.
(a) Mind walker exoskeleton (b) SJTU exoskeleton (c) ankle exoskeleton.

3. Exoskeleton classification

In recent years, researches into lower extremity exoskeletons have become a hot topic. Several organizations all over the world have designed impressive exoskeletons for power augmentation, differing significantly in performance and in the technology used.

Exoskeletons may be classified as intended to augment human capabilities, such as load capacity or ambulatory speed, or to increase human endurance, by lowering the metabolic demand of a given activity. While the ultimate intent of exoskeletons described in most literature is to reduce muscle activation and increase endurance in running, this considers both types of devices as the division is frequently blurred. For instance, a device intended to reduce the metabolic demand of a movement may alternatively permit the execution of that movement at higher speed for a given metabolic demand. Moreover, some orthotic devices, intended to restore lost functionality, may be thought of as exoskeletons.

So the exoskeleton can be broadly categorized according to their usage of power into three groups: passive exoskeleton, quasi-passive exoskeletons and powered exoskeletons which are considered as active devices [7] [9].

Passive exoskeletons require no energy source and generally consist of linkages, springs, and dampers, Passive exoskeletons are often lightweight, but due to their lack of power supply and electronics, their controllability is limited [10].

Active devices, in contrast, add energy to the human gait cycle, usually through motors or hydraulic cylinders, Power supply is being one of the most limiting factors but of great importance in the exoskeleton design. Without an on board power supply for the exoskeleton, it would be limited only to indoor applications where power can be obtained directly from the wall. However, as battery power has improved over the years, the invention has brought about more compact and higher capacity batteries which are capable of sustaining the exoskeleton during the course of its service. The HAL suit is powered by battery packs of lithium and nickel metal hydride origin, which currently is capable of sustaining the lower and upper part of the exoskeleton for 2 hours and 40 minutes on a single full charge [11].

Quasi-passive devices lie between, they are unable to inject energy into the gait cycle, but nonetheless requiring a power supply, usually to operate electronic control systems, clutches, or variable dampers. Typically, though not necessarily, the power requirement of a quasi-passive device is small.

Furthermore, exoskeletons can be classified according to system containment to tethered or autonomous. Tethered exoskeletons require a connection such as, pressurized lines, electrical wires to an external mass not worn on the body, typically an energy source or control hardware. Unlike tethered exoskeletons, the entire system of an autonomous exoskeleton is worn by the user, And thus, autonomous exoskeletons are typically not limited to a laboratory setting [10].

Finally exoskeletons may be described as their primary action, whether in series or in parallel with the wearer's limbs [12].

Based on the part of the human body the exoskeleton supports, exoskeletons can be classified as upper extremity exoskeletons, lower extremity exoskeletons (LEEs), full body exoskeletons, and specific joint support exoskeletons [13] [14].

The lower extremity exoskeletons (LEEs) categorized in three main applications: Gait rehabilitation, human locomotion assistance, and human strength augmentation [15].

The first application focuses on gait rehabilitation (helping patients with mobility disorders in the rehabilitation of musculoskeletal strength, motor control, and gait). Exoskeleton based rehabilitation also releases the heavy burden of therapists in traditional physical therapy [16]. Robotic exoskeletons have been developed to increase the efficiency of the rehabilitation therapy. Robotic exoskeletons are capable of providing more intensive patient training, better quantitative feedback and improved functional outcomes for patients compared to manual therapy. In this review, the emphasize is placed on treadmill based and over ground exoskeletons for rehabilitation [17].

The second application is human locomotion assistance, which is targeted at paralyzing patients who have lost motor and sensory function in their lower limbs. Assistance from exoskeletons enable these patients to regain the ability to stand up, sit down, and walk, just as an able bodied person [18] [19],

The third application of exoskeletons is aimed at enhancing the physical abilities of able-bodied humans (human strength augmentation) [20].

4. Comparison of the types of exoskeleton

1) The numbers of dof: each exoskeleton has a degree of flexibility can be identified by a dof. Some exoskeleton designed, lacked dof (Yagn exoskeleton) [10] [11],and some have high flexibility reaches to 30 dof (Hardiman) [7],BLEEX is 7 dof (3 at hip, 1 at knee and 3 at ankle) [25] [27], and ROBOKNEE is 1 dof.

2) The usage of power: Some exoskeletons are active exoskeleton (HAL-3, BLEEX, partial exoskeleton and ankle exoskeleton) [26] [25] [27] [54].

And the rest is passive exoskeleton (gravity balance exoskeleton, spring walker) [29] [55], Quasi-passive devices lie between two types (moon walker) [45].

SJTU-EX integration between active and passive exoskeleton (4 actuated joint and 2 passive joints) [1].

3) Wearing Body: some exoskeletons are designed to cover the full body, such as HARDIMAN model [1], also there is a design that can be worn only in the ankle area like ANKEL exoskeleton [54], or in knee area like ROBOKNEE exoskeleton [5], and gravity balance exoskeleton designed to cover the total leg area of the hip, knee, ankle [29].

4) The way of wearing the exoskeleton relative to the body: HAL-3 designed to wear in parallel with the leg [26]. While the spring walker model is designed to wear in series with the legs [55].

5) Tethered or autonomous: In rehabilitation exoskeleton some are designed to be overground walking and other designed for treadmill training only [56] [10].

5. Selection and development

Passive exoskeletons that assist with human locomotion are often lightweight and compact, but are unable to provide net mechanical power to the exoskeletal wearer. In contrast, powered exoskeletons often provide biologically appropriate levels of mechanical power, but the size and mass of their actuator/power source designs often lead to heavy and unwieldy devices [57].

If the use of an exoskeleton for satisfactory reasons for any of the people who suffer from muscle weakness or pain of joints, Then one must take into account the design of the exoskeleton so that it should be a relatively light weight, because it is not reasonable to fatigue a patient with extra weighing arguing the desert to walk, So in this case it is more preferable to use passive exoskeletons.

The passive exoskeleton is lighter because it contains only mechanical parts and at the same time will be cheaper so it can be available to the general public.

And If the exoskeleton is used to improve the efficiency of the healthy human for carrying heavy weights, then a powered exoskeleton can be used , Because in this case the person is able to carry an exoskeleton, even if it is heavyweight, as in military application [20] [58], Firemen and workers in mega ships and aircraft industry.

The powered exoskeleton uses pneumatic cylindrical and/or motors, and it may be computerized, so the powered exoskeleton is considered expensive [59].

Exoskeletons have been developed in a way to amplify human strength by applying assistive torques to the joints and/or by supporting a payload for the wearer. Many of these investigations have focused on fully actuated systems that are energetically expensive, requiring a large power supply with frequent refueling or recharging. There are some exoskeletal designs that comprise passive and quasi-passive mechanisms to enhance mechanical energy storage and exchange between the exoskeleton and the wearer.for passive exoskeletons improvements can be attained by carefully selecting spring engagement, joint angles and stiffnesses, we anticipate that the work output of the human joints can be effectively lowered during exoskeletal walking [60].

In general, any development or improvement on exoskeleton should be Focus on the following points:

1) Less power consumption.
2) Better cosmetics.
3) Lighter weight and compactness.

4) Cheaper.
5) Less noise.
6) High efficiency.
7) More balanced.
So the development of powerful, efficient, adaptable, lightweight and low-cost mechanisms is imperative in achieving applicable exoskeletons and fulfilling the goal of integration of robots into our daily lives [61].

6. Conclusion
This paper presents a review of working design principles and prototypes for different exoskeletons. Some of them are active exoskeletons with DC motors with the harmonic drive and pneumatic artificial muscle (PAM). This combination takes advantages of both the harmonic drive and the pneumatic artificial muscle. It provides both high accuracy position control and high ratio of strength to weight. This type is applied to improve the efficiency of the human sense of carrying heavy weights. So the factor of exoskeleton weight is not considered an obstacle to design the machine. Other types are fully passive, i.e., does not use any actuators, but still takes away the gravity load from the joints. It is adjustable to the subject wearing it [59], [62]. And the Quasi passive lies between the two types, it means unable to inject energy into the gait cycle, but nonetheless requiring a power supply, the power requirement of a quasi-passive device is small. The last two types can be used to re walk the patient, so the weight factor is important in this case, so we must take into account the weight factor into consideration, in which lightweight designs are required so as not to overtax the patient extra weight.

References
[1] Dollar, A., & Herr, H. (2008). Lower Extremity Exoskeletons and Active Orthoses: Challenges and State-of-the-Art, *24* (1), 144–158.
[2] Zoss, A., & Kazerooni, H. (2005). IMECE2005-80129, 1–9.
[3] Pons, J., Moreno, J., Brunetti, F., & Rocon, E. (2007). Lower-Limb Wearable Exoskeleton. *Rehabilitation Robotics,* (August), 471–498. http://doi.org/10.5772/5176
[4] Cenciarini, M., & Dollar, A. M. (2011). Biomechanical considerations in the design of lower limb exoskeletons. *IEEE International Conference on Rehabilitation Robotics*, (October). http://doi.org/10.1109/ICORR.2011.5975366.
[5] Pratt, J. E., Krupp, B. T., Morse, C. J., & Collins, S. H. (2004). The RoboKnee: an exoskeleton for enhancing strength and endurance during walking. *IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA '04. 2004*, *3*(April), 2430–2435. http://doi.org/10.1109/ROBOT.2004.1307425
[6] Kinesiology, D., Ave, W., Mi, A. A., & Ferris, D. P. (2013). NIH Public Access, *17*(1), 1–17. http://doi.org/10.1109/TNSRE.2008.2008285.Medial
[7] Miao, Y., Gao, F., & Pan, D. (2013). Mechanical design of a hybrid leg exoskeleton to augment load-carrying for walking. *International Journal of Advanced Robotic Systems*, *10*. http://doi.org/10.5772/57238
[8] Onen, U., F.M. Botsali, M. Kalyoncu, M. Tinkir, N. Yilmaz, Y. Sahin, 2013. Design and Actuator Selectionof a Lower Extremity Exoskeleton, IEEE/ASME Transactions on Mechatronics, 99: 1-10..
[9] Elliott, G. (2012). Design and evaluation of a quasi-passive robotic knee brace: on the effects of parallel elasticity on human running. Retrieved from http://dspace.mit.edu/handle/1721.1/71474
[10] Mooney, L. M., & Herr, H. M. (2015). Biomechanical walking mechanisms underlying the metabolic reduction caused by an autonomous exoskeleton. *Journal of Neuroengineering and Rehabilitation*, 1–12. http://doi.org/10.1186/s12984-016-0111-3
[11] Hong, Y. W., King, Y., Yeo, W., Ting, C., Chuah, Y., Lee, J., … Lumpur, K. (2013). Lower Extremity Exoskeleton : Review and Challenges Surrounding the Technology and its Role in Rehabilitation of Lower Limbs. *Australian Journal of Basic and Applied Sciences*, *7*(7), 520–524.
[12] For, A., & Walking, F. (1890). No. 420,179.' Patented Jan. 28, 1890.v, (420).
[13] Kim YS, Lee J, Lee S, Kim M. A force reflected exoskeleton- type master arm for human-robot interaction. IEEE Trans Syst Man Cybern A Syst Hum 2005;35:198e212.
[14] Agrawal A, Banala SK, Agrawal SK, Binder-Macleod S. Design of a two degree-of-freedom ankle-foot orthosis for robotic rehabilitation. IEEE International Conference on Robotic Rehabilitation. Chicago, IL, USA: IEEE; 2005. p. 41e4.
[15] Law, S., Qin, L., & Liao, W. (2015). ScienceDirect Recent developments and challenges of lower extremity exoskeletons. *Journal of Orthopaedic Translation*, *5*(October), 1–12. http://doi.org/10.1016/j.jot.2015.09.007
[16] Alcobendas-Maestro M, Escları ´n-Ruz A, CasadoLo´pez RM,Mun˜oz-Gonza ´lez A, Pe ´rezMateos G, Gonza ´lez-Valdiza´n E, et al. Lokomat robotic- assisted versus overground training within 3 to 6 months of incomplete spinal cord lesion ran- domized controlled trial. Neurorehabil Neural Repair 2012;26: 1058e63.

[17] Chen, G., Chan, C. K., Guo, Z., & Yu, H. (2013). A Review of Lower Extremity Assistive Robotic Exoskeletons in Rehabilitation Therapy. *Critical Reviews in Biomedical Engineering*, *41*(4-5), 343–363. http://doi.org/10.1615/CritRevBiomedEng.2014010453
[18] Tsukahara A, Kawanishi R, Hasegawa Y, Sankai Y. Sit-to-stand and stand-to-sit transfer support for complete paraplegic patients with robot suit HAL. Adv Robot 2010;24: 1615e38.
[19] Esquenazi A, Talaty M, Packel A, Saulino M. The ReWalk powered exoskeleton to restore ambulatory function to in- dividuals with thoracic-level motor-complete spinal cord injury. Am J Phys Med Rehabil 2012;91:911e21.
[20] Zoss AB, Kazerooni H, Chu A. Biomechanical design of the Berkeley lower extremity exoskeleton (BLEEX). IEEE ASME Trans Mechatron 2006;11:128e38.
[21] For, A., & Walking, P. (1890). I QE HW - : is ‘ a, (438).
[22] N. J. Mizen, “Powered exoskeletal apparatus for amplifying human strength in response to normal body movements,” U.S. Patent 3 449 769, 1969.
[23] Vukobratovi, M., Borovac, B., Surla, D., Stokid, D. (1990), Biped Locomotion: Dynamics, Stability, Control, and Application, Springer-Verlag, Berlin, pp. 321-330. 98
[24] Valiente, A., & Herr, H. (2005). Design of a Quasi-Passive Parallel Leg Exoskeleton to Augment Load Carrying for Walking by. *Security*, (2003), 1–114. Retrieved from http://biomech.media.mit.edu/publications/ValienteThesis.pdf
[25] Kazerooni, H. (1996), 'The human power amplifier technology at the University of California, Berkeley', Robotics Autonomous Systems pp. 19:179-187.Kazerooni
[26] Kawamoto, H. & Sankai, Y. (2002), 'Power assist system HAL 3 for gait disorder person', Computers Helping People with Special Needs 81h International Conference, ICCHP 2002. Proceedings (Lecture Notes in Computer Science Vol. 2398) 196-203
[27] Kazerooni, H., Racine, J.L., Huang, L., & Steger, R. (2005), 'On the Control of the Berkeley Lower Extremity Exoskeleton (BLEEX)', IEEE International Conference on Robotics and Automation pp. 4364-4371.Linear
[28] (Huang, G.T. (2004), 'Demo: Wearable Robots', Technology Review, pp. July/August 2004.18) Inman
[29] Agrawal, S. K., Banala, S. K., & Fattah, A. (2006). A Gravity Balancing Passive Exoskeleton for the Human Leg. *Robotics: Science and Systems* , (302). Retrieved from D:\PhD\Reference_Managers\JabRef_Library\Sources\A Gravity Balancing Passive Exoskeleton for the Human Leg.pdf
[30] Banala, S. K., Agrawal, S. K., Fattah, A., Krishnamoorthy, V., Hsu, W. L., Scholz, J., & Rudolph, K. (2006). Gravity-balancing leg orthosis and its performance evaluation. *IEEE Transactions on Robotics*, *22*(6), 1228–1239. http://doi.org/10.1109/TRO.2006.882928
[31] Kong KC, Jeon D. Design and control of an exoskeleton for the elderly and patients. IEEE- Asme TMech. 2006; 11(4): p.428-32.
[32] Carse B, Meadows B, Bowers R, Rowe P. Affordable clinical gait analysis: An assessment of the marker tracking accuracy of a new low-cost optical 3D motion analysis system. Physiotherapy. 2013. In Press.
[33] Banala SK, Agrawal SK, Scholz JP. Active Leg Exoskeleton (ALEX) for gait rehabilitation of motor-impaired patients. Proceedings of the IEEE 10th International Conference on Rehabilitation Robotics (ICORR); 2007 Jun 13-15; Noordwijk aan Zee, The Netherlands. 2007. p.401-7.
[34] Agrawal SK, Banala SK, Fattah A, Sangwan V, Krishnamoorthy V, Scholz JR, et al. Assessment of motion of a swing leg and gait rehabilitation with a gravity balancing exoskeleton. IEEE T Neur Sys Reh. 2007;15(3):410-20.
[35] Wang P, Low KH, Tow A. Synchronized Walking Coordination for Impact-less Foot-pad Contact of an Overground Gait Rehabilitation System: NaTUre-gaits. Proceedings of the IEEE International Conference on Rehabilitation Robotics (ICORR), 2011 June 29 -July 1, Zurich, 2011.p.1-6.
[36] Wang P, Low KH, Tow A, Lim PH. Initial System Evaluation of an Overground Rehabilitation Gait Training Robot (NaTUre-gaits). Adv Robotics. 2011;25(15):1927-48.
[37] Winfree KN, Stegall P, Agrawal SK. Design of a Minimally Constraining, Passively Supported Gait Training Exoskeleton: ALEX II. Proceedings of the 2011 IEEE International Conference on Rehabilitation Robotics (ICORR); 2011 Jun 29-Jul 1; Zurich, Switzerland. 2011. p.1-6.
[38] Kim SH, Banala SK, Brackbill EA, Agrawal SK, Krishnamoorthy V, Scholz JP. Robot- assisted modifications of gait in healthy individuals. Exp Brain Res. 2010;202(4):809-24.
[39] Stegall P, Winfree KN, Agrawal SK. Degrees-of-Freedom of a Robotic Exoskeleton and Human Adaptation to New Gait Templates. Proceedings of the 11th IEEE International Conference on Robotics and Automation (ICRA); 2012 May 14-18; Saint Paul, MN. 2012. p.4986-4991.
[40] Dollar, A. M., & Herr, H. (2008). Design of a quasi-passive knee exoskeleton to assist running. *2008 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS*, 747–754.

http://doi.org/10.1109/IROS.2008.4651202
[41] Stauffer Y, Allemand Y, Bouri M, Fournier J, Clavel R, Metrailler P, et al. The WalkTrainer—a new generation of walking reeducation device combining orthoses and muscle stimulation. IEEE T Neur Sys Reh. 2009;17(1):38-45.
[42] Sawicki, G. S., & Ferris, D. P. (2009). A pneumatically powered knee-ankle-foot orthosis (KAFO) with myoelectric activation and inhibition. *Journal of Neuroengineering and Rehabilitation*, *6*, 23. http://doi.org/10.1186/1743-0003-6-23
[43] Chin, R., Hsiao-Wecksler, E. T., Loth, E., Kogler, G., Manwaring, S. D., Tyson, S. N., … Gilmer, J. N. (2009). A pneumatic power harvesting ankle-foot orthosis to prevent foot-drop. *Journal of Neuroengineering and Rehabilitation*, *6*, 19. http://doi.org/10.1186/1743-0003-6-19
[44] Aguirre-Ollinger, G., Colgate, J. E., Peshkin, M. a., & Goswami, A. (2011). Design of an active one-degree-of-freedom lower-limb exoskeleton with inertia compensation. *The International Journal of Robotics Research*, *0*(0), 1–14. http://doi.org/10.1177/0278364910385730
[45] Benoit, M., & Dombre, E. (2010). MoonWalker, a Lower Limb Exoskeleton able to Sustain Bodyweight using a Passive Force Balancer, 2215–2220.
[46] Hussain S, Xie SQ, Jamwal PK, Parsons J. An intrinsically compliant robotic orthosis for treadmill training. Med Eng Phys. 2012;34(10):1448-53.
[47] Hussain S, Xie SQ, Jamwal PK. Robust Nonlinear Control of an Intrinsically Compliant Robotic Gait Training Orthosis. IEEE T Syst, Man, Cybern. 2013;43(3):655-65.
[48] Zeilig G, Weingarden H, Zwecker M, Dudkiewicz I, Bloch A, Esquenazi A. Safety and tolerance of the ReWalk (TM) exoskeleton suit for ambulation by people with complete spinal cord injury: A pilot study. J Spinal Cord Med. 2012;35(2):96-101.
[49] Kim, J. H., Han, J. W., Kim, D. Y., & Baek, Y. S. (2013). Design of a walking assistance lower limb exoskeleton for paraplegic patients and hardware validation using CoP. *International Journal of Advanced Robotic Systems*, *10*. http://doi.org/10.5772/55336
[50] Ekso Bionics. (2012). Retrieved 2 September, 2013, from http://www.eksobionics.com/ekso
[51] Quintero HA, Farris RJ, Hartigan C, Clesson I, Goldfarb M. A Powered Lower Limb Orthosis for Providing Legged Mobility in Paraplegic Individuals. Top Spinal Cord Inj Rehabil. 2011;17(1):25-33.
[52] Turk R, Obreza P. Functional Electrical-Stimulation as an Orthotic Means for the Rehabilitation of Paraplegic Patients. Paraplegia. 1985;23(6):344-8.
[53] Mind control orthosis and VR training environment for walk empowering (MINDWALKER). Retrieved 1 October, 2013, from https://www.mindwalker-project.eu/
[54] Witte, K. A., Zhang, J., Jackson, R. W., & Collins, S. H. (2015). Design of Two Lightweight, High-Bandwidth Torque-Controlled Ankle Exoskeletons, 1223–1228.
[55] Patent, U. S. (1991). @ QQ.
[56] Cheng, P. Y., & Lai, P. Y. (2013). Comparison of exoskeleton robots and end-effector robots on training methods and gait biomechanics. *Lecture Notes in Computer Science (including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *8102 LNAI*(PART 1), 258–266. http://doi.org/10.1007/978-3-642-40852-6-27
[57] Mooney, L. M., Rouse, E. J., & Herr, H. M. (2014). Autonomous exoskeleton reduces metabolic cost of human walking Autonomous exoskeleton reduces metabolic cost of human walking, *11*(1), 1–5. http://doi.org/10.1186/1743-0003-11-151
[58] Chu A, Kazerooni H, Zoss A. On the biomimetic design of the Berkeley Lower Extremity Exoskeleton (BLEEX). IEEE International Conference on Robotics and Automation. Barcelona, Spain: IEEE; 2005. p. 4345e52.
[59] Aguilar-Sierra, H., Yu, W., Salazar, S., & Lopez, R. (2015). Design and control of hybrid actuation lower limb exoskeleton. *Advances in Mechanical Engineering*, *7*(6), 1–13. http://doi.org/10.1177/1687814015590988
[60] Chin, R., Hsiao-Wecksler, E. T., Loth, E., Kogler, G., Manwaring, S. D., Tyson, S. N., … Gilmer, J. N. (2009). A pneumatic power harvesting ankle-foot orthosis to prevent foot-drop. *Journal of Neuroengineering and Rehabilitation*, *6*, 19. http://doi.org/10.1186/1743-0003-6-19
[61] Peternel, L., Tomoyuki, N., Petric, T., Ude, A., Morimoto, J., & Babic, J. (2015). Adaptive control of exoskeleton robots for periodic assistive behaviours based on EMG feedback minimisation. *IEEE Transactions on Mechatronics*, *accepted f*, 1–26. http://doi.org/10.1371/journal.pone.0148942
[62] Agrawal, S. K., Banala, S. K., & Fattah, A. (2006). A Gravity Balancing Passive Exoskeleton for the Human Leg. *Robotics: Science and Systems*, (302). Retrieved from D:\PhD\Reference_Managers\JabRef_Library\Sources\A Gravity Balancing Passive Exoskeleton for the Human Leg.pdf
[63] Kawabata T, Satoh H, Sankai Y. Working posture control of robot suit HAL for reducing structural stress.

IEEE Interna- tional Conference on Robotics and Biomimetics. Guilin, China: IEEE; 2009. p. 2013e8.
[64] Sankai Y. HAL: hybrid assistive limb based on Cybernics. Ro- botics research. Germany: Springer: Berlin and Heidelberg; 2011. p. 25e34.
[65] Taketomi T, Sankai Y. Stair ascent assistance for cerebral palsy with robot suit HAL. IEEE/SICE International Symposium on System Integration (SII). Fukuoka, Japan: IEEE; 2012. p. 331e6.