Lower Limb Exoskeletons: A Brief Review

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Abstract— The elderly population in our society is increasing and hence societal issues related to ageing problems are also increasing. One of the key issues facing elderly persons relates to personal mobility which is essential for independence and good quality of life. With advances in technology, conventional methods like walkers, crutches and wheel chairs for providing mobility are being overtaken by wearable robots, commonly known as exoskeletons. This technology represents the future of mobility solutions for the elderly. Many research institutes and commercial undertakings are putting efforts to come up with a general purpose exoskeleton able to meet the needs but we are still far from having an effective and affordable solution developed to the masses. The paper presents a review of the exoskeletons produced to date describing their constructional and technological features and the remaining gaps in technology. Further, the paper discusses the challenges that need to be addressed and the future trends in the exoskeleton domain.

Key words: Exoskeletons, Wearable Robotics, Lower-Limb Exoskeletons, Assistive Robotics

I. INTRODUCTION

According to UN population percentage report [1], the number of people above the age 60 will rise steeply to about one billion in 2050 as shown in Fig.1. These one billion will include healthy aged persons as well as people suffering from heart diseases, spinal cord injuries and other old age problems which will hinder their natural mobility. People in this age tend to lose their independence and have to depend on others for their basic necessities and for carrying out essential daily chores.

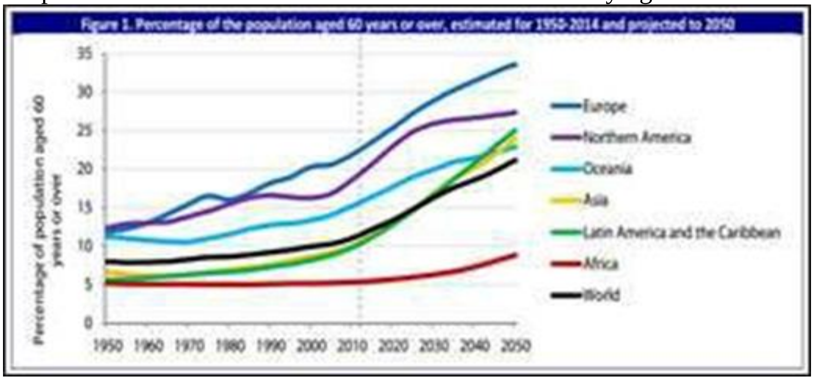

Fig. 1: UN's ageing population statistics [1]

Currently, devices like crutches, walkers and wheelchairs have been used to assist in personal mobility or even in rehabilitation applications but these devices are not very effective. They could not solve basic problems faced during the use of these devices even if the people do not use the devices but employ an assistant or a family member for helping them as shown in Fig.2.

The major problems faced by elderly people are:

- Inability to sit, stand, perform transfers and to walk, o need for personal assistance at home,
- Risk losing independence, o reduced quality of life,
- Financial problems to employ carers.

Stroke is also a major trauma that can occur leading to an inability to walk and often the affected person has one or more limbs paralyzed on one side of the body as the affected area on the brain can no longer function normally [2]. When the lower limbs are affected, a rehabilitation treatment is required to restore gait function and regain the capacity to walk independently.

Fig. 2: Conventional personal mobility solutions

A number of individual rehabilitation treatment approaches have been proposed to improve overall walking ability. The recovery process to regain lost mobility capability is more effective during the first 3 to 6 months after the stroke onset and it is highly dependent on the individual. At this point, intervention programs can be initiated to retrain the ability to produce strong movements and functional trajectories while performing activities of daily living. The most important task to be relearned, as claimed by patients suffering from stroke, is the possibility to walk again, in order to return to a normal life when possible [2]. Task oriented and highly repetitive practice motions are recognized as interventions for the restoration of gait function. Recently, in an attempt to improve the recovery A number of individual rehabilitation treatment approaches have been proposed to improve overall walking ability. The recovery process to regain lost mobility capability is more effective during the first 3 to 6 months after the stroke onset and it is highly dependent on the individual. At this point, intervention programs can be initiated to retrain the ability to produce strong movements and functional trajectories while performing activities of daily living. The most important task to be relearned, as claimed by patients suffering from stroke, is the possibility to walk again, in order to return to a normal life when possible [2]. Task oriented and highly repetitive practice motions are recognized as interventions for the restoration of gait function. Recently, in an attempt to improve the recovery

Fig. 3: From conventional methods to exoskeletons

The term exoskeleton coming from the Greek words “exo” = outer and “skeletos” = skeleton, is an external structure that supports and protects an animal’s/human’s body, in contrast to the internal skeleton of, for example, a human. Powered exoskeletons (hereafter referred as robotic exoskeletons or just exoskeletons) are wearable robots attached to the wearer’s limbs, in order to replace or enhance their movements. These should be compliant with the users’ movements and deliver at least part of the power necessary to accomplish the desired motions [4].

Major advantages of exoskeletons developed for paraplegics and elderly are to:

- Prevent muscle atrophy by daily use and enhance recovery in case of damage.
- Increase autonomy of persons by allowing them to do things independently.
- Improve the psychological state of the user.
- Adapt to all environments for normal daily motions such as walking and stair climbing.
- Reduce the energy required to move the primary joints (knee/hip/ankle) as the load is taken by the exoskeleton
- Target specific joints for rehabilitation purpose.

Here our major concern is the independence of elderly persons as shown in Fig.4.

Other important uses of powered exoskeletons are load augmentation. For decades, engineers and scientists have dreamed to bring to reality an exoskeleton that could boost human strength, turning an ordinary person into a “superhuman” but to technological limitations, practical models could not been developed until a few years ago. With the current miniaturization, powerful computing and communication systems, it is now possible to develop advanced robotic solutions where new technology using potent actuators that can be embedded in the devices. New power sources have also been investigated and are now making possible the ability to increase the operational times of the devices without recharging. All these technological advancements are giving rise to the possibility of realizing effective and affordable exoskeletons for normal daily life.

Fig. 4: Self-care of the elderly via exoskeletons

II. EXOSKELETONS: A PARADIGM

According to the Merriam-Webster dictionary, an exoskeleton is 'an artificial external supporting structure'. It closely fits the body of the wearer. Here we will deal with powered exoskeletons starting from the first exoskeleton realized to the latest ones. In this section, a state-of-the-art review on exoskeleton devices is presented. The major focus of the exoskeletons realized to date is on lower limb exoskeletons for paraplegics and elderly persons. Figure 5 shows a classification of these exoskeletons into some basic groups.

A. Load Carrying Augmentation:

These are exoskeletons used in military purposes [4] or for workers carrying out heavy duty tasks. Some major exoskeletons developed are discussed next.

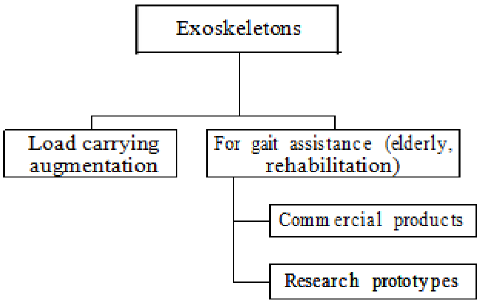

Fig. 5: Basic Classification of Exoskeletons

1) Bleex

Berkeley Lower Extremity Exoskeleton [5] is a heavy load carrying exoskeleton having its own on-board battery. Each leg has seven degrees-of-freedom (DOFs) as shown in Fig. 6 with 3 DOFs at the hip, 1 at the knee, and 3 at the ankle. Out of these, four are actuated: hip flexion/extension, hip abduction/adduction, knee flexion/extension, and ankle flexion/extension. Out of the remaining un-actuated joints, the ankle inversion/ eversion and hip rotation joints are spring-loaded, and the ankle rotation joint is free-spinning. The kinematics and actuation requirements of the exoskeleton were designed by assuming behavior similar to that of a 75 kg human and utilizing clinical gait analysis data for walking [6]. It follows the strategy based on sensitivity amplification controller. Inverse dynamics of Bleex in the sagittal plane is modeled on three different gait phases. Interesting features of the kinematic design of the exoskeleton include a hip "rotation" joint that is shared between the two legs of the exoskeleton, and therefore, does not intersect with the wearer's hip joints.

2) Body Extender

This is an exoskeleton [2] used for increasing the load carrying capacity for longer durations. Its payload can be transferred to the ground using the same technique as used in Bleex. It has 22 DOFs with 6 DOFs in each leg.

3) MIT Exoskeleton

This exoskeleton is designed using a pelvic harness technique [4] in which the load of the bag pack is transferred to the ground. It uses concepts similar to human walking for carry the load and supporting the movement of the body.

Fig. 6: Bleex [5]

It means that the load does not passes through the body of the wearer but goes directly to the ground due to linkages provided in the pelvic area. The actuation of the hip and knee depend on the gait cycle, and the controller is designed using human body dynamics data. The device does not use actuators to add power at the joints but is based on the release of energy stored in springs [7]. A spring loaded joint is used in the 3 DOFs hip in which energy is stored during extension and then released during flexion. This spring mechanism allows the user to freely swing the hip in the flexion direction.

4) Naeies

The Naval Aeronautical Engineering Institute Exoskeleton Suit was developed [8] to carry heavy loads in different terrains as shown in Fig. 7 and to increase speed for military application. It has six DOF in each leg, two of which are at hip, one at the knee and three at the ankle. Its hip joint motion is done using a spring. Multi axes force and torque sensors are used to sense the change in force and torque while walking [9] and DC motors are used as actuators in this suit. It is used in military purposes to increase speed. It is also foreseen to be used in mountaineering, firefighting and disaster relief situations.

5) Sarcos Exoskeleton

This is a powered exoskeleton [10] which provides autonomous power supply to the user. It has rotary hydraulic actuators and uses force sensing to control the motion. The wearer cannot bend his feet due to a metal plate that is installed behind it which includes force sensing elements. This is a very powerful suit as shown in Fig.8 targeted for military purposes.

Fig. 7: NAEIES [8]

Fig. 8: Sarcos Exoskeleton [10]

The exoskeleton uses a variety of sensors for determining force and position of the system [2]. The sensors are connected via wires to distributed computer processors in each joint, which prompt the actuators to deliver up to 200 kg per square centimeter of force through high-pressure hydraulics.

6) Hardiman

This is a full body powered exoskeleton [11] used for increasing the power and load carrying capacity. It is powered hydraulically and can increase the strength of the wearer by 25%. It was not very successful due to balancing problems.

7) Pitman

This is a defence funded project [11], to enhance the power of US soldiers. Its helmet consists of a network of sensors to scan the brain. The main problem was that it had issues of power supply and deployment techniques so it was not very successful and has been terminated.

B. Exoskeletons for Gait Assistance

Some of the most significant works in this field are discussed and analyzed. These are some of the most significant lower limb exoskeletons which are currently commercially available in the market.

1) Hal

Hybrid Assistive Limb (HAL) is a wearable exoskeleton which comes in different models. The various models are designed for different applications, including rehabilitation, heavy labor support, rescue support and also entertainment. It is also built in several versions: full body, lower body and one leg versions [13]. A single leg version of HAL has been developed to support the walking of persons with hemiplegia. A new version of this device, HAL5 (full body) targets paraplegic users. HAL is developed by Tsukuba University and Cyberdyne, Japan. In February 2013, HAL received a global ISO safety certificate conforming to the ISO 13482 DIS standard, becoming the first exoskeleton to achieve this goal. Different Hal models have subsequently been certified to ISO 13482 (Safety standard for personal care robots) published in 2014 [21], and which includes such exoskeletons defined as physical assistant robots. The lower body model of the device weights about 15 kg and the full body model about 23 kg as shown in Fig.9. It is battery operated and has power autonomy to operate for approximately 2.5 hours. Hip and knee joints actuators are based on DC servo motors and harmonic drive gears, while the ankle joint is passively controlled. HAL has a control unit carried in a backpack by the user. This unit runs on a Linux operational system and communicates to a remote monitoring computer by wireless Local Area Network. The actuation mechanisms of HAL are based on surface electromyography (sEMG) signals [20] with surface electrodes attached to the skin that provide the system the wearer's intended movements. HAL is able to provide power assistance, which may make it difficult for severely hemiplegic patients to perform activities using their own muscles. This could lead to instability, resulting in decreases in stride length and walking speed.

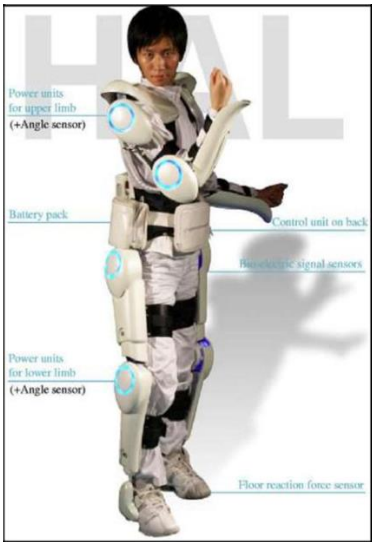

Fig. 9: HAL [15]

Fig. 10: ReWalk [9]

2) ReWalk^{TM}

ReWalk as shown in Fig.10 is a wearable motorized medical suit from Argo Medical Technologies Inc. [16] that can be used for therapeutic activities. ReWalk exoskeleton has hip and knee movements powered in the sagittal plane. It comprises a light wearable brace support suit, which integrates DC motors at the hip and knee joints, rechargeable batteries, an array of sensors and a computer control system. The device is powered by rechargeable batteries intended for all-day use and overnight charging. It goes on a backpack carried by the patient. The device is customized and sized for each patient [19]. In this device variations in the user's center of gravity are detected to initiate and maintain walking processes. The user also has a remote control placed in his/her arm, like a watch. With this interface, it is possible to start different tasks, such as sit-to-stand, waking or climbing stairs. ReWalk is intended for persons with lower limb disabilities that have suffered injuries in the spinal cord. It cannot keep balance control, so the user should always be supported by crutches. Argo Medical sells two models of its exoskeleton, called Rewalk Rehabilitation and ReWalk Personal with FDA approval. The first is intended for clinical use and has been deployed in rehabilitation centers across Europe, Israel and United States. The second model is intended for personal use as an assistive system. In 2012, Argo started selling ReWalk Personal model in Europe.

3) Vanderbilt Exoskeleton

The Vanderbilt exoskeleton is a prototype developed in the University of Vanderbilt (Tennessee, United States) in the Center for Intelligent Mechatronics [17]. The device shown in Fig.11 weights ≈12 kg and, like the other exoskeletons discussed here, it has actuation only at the hip and knee joints. Ankle and foot supports are not present and it has to be used with an off-the-self ankle-foot orthosis. The device is powered by brushless DC motors through a 24:1 gear reduction, which provides a maximum continuous torque of 12 Nm for hip and ankle joints. Potentiometers are used as angular position sensors. A lithium polymer battery of 3.9 Ah provides one hour of power autonomy for continuous walking with the device at a speed of 0.8 km/h. The control is based on postural information measured on the device that the authors claim enables the wearer to control the device in a safe, reliable and intuitive manner. The exoskeleton is designed to provide gait assistance to persons with paraplegia. It is modular and split into three pieces, which makes it easy of putting on and taking off, even if the user is in a wheelchair. Wearer weight limit is 91 kgs.

Fig. 11: Vanderbilt Exoskeleton [17]

Fig. 12: eLEGS [18]

4) eLEGS

Ekso Bionics (earlier Berkeley Bionics) is a US company that originally developed exoskeletons for military use. In October 2010, they have unveiled a rehabilitation version called eLEGS (Exoskeleton Lower Extremity Gait System) that in 2011 was renamed as Ekso [18]. Ekso weights approximately 20 kg and has a maximum speed of 3.2 km/h with a battery life of 6 hours. It can execute sit-to-stand and stand-to-sit operations and support walking in a straight line. Ekso as shown in Fig.12 is currently going under development to become lighter and more adaptable. Following clinical trials it received FDA approval to market the exoskeleton for hospital use in 2012 in USA. The device can be commanded by a user interface that can control the device step by step. Like the ReWalk system, Ekso also needs crutches to support weight balancing of the wearer because of the imbalance which is created during the initial jerk in the motions.

III. CHALLENGES

After studying the various exoskeletons which have been developed and also looking into their constructional and usage specifications, a comparison is carried out and the results are presented in Table 1.

This comparison is limited to exoskeletons for gait assistance and informs about the pros and cons and identifies key improvement areas. The major challenges include better power sources [23] and control strategies [22] for quieter and smooth operation of the exoskeletons. It is seen that mostly DC batteries are used as the actuators.

Other challenges include the overall weight and cost of the exoskeleton. The need for support crutches is also a concern as it gives a feel of dependency to the wearer, so it needs to be eliminated. The torque variation techniques and the motion reversal methods need to be looked into as the mechanical/electronic components used for this purpose put a significant effect on the cost of the device, for example the price of the Vanderbilt exoskeleton is high due to the costly harmonic drives used for controlling the motor torques. Same is the case with motion reversal required for abduction/adduction of the knee joints. Engagement/ disengagement of the motor with the knee joint is not provided in any exoskeleton, providing this will help the user make minor adjustments and movements while he/she is sitting without removing the exoskeleton completely. The authors are currently working on developing low-cost exoskeletons which can overcome these problems and serve as general purpose devices for elderly persons.

Suit	Weight (kg)	Approx. Cost ($)	Support Crutches	Motion Reversal	Actuators Used	Torque Variation
HAL	15	15,000	No	Slow	DC servo motors	EMG Control
ReWalk^{TM}	24	69,500	Yes	Very Slow	DC motors	Micro Controller
Vanderbilt	12	140,000	Yes	Slow	DC brushless	Harmonic Drives
eLEGS	20	50,000	Yes	Moderate	Linear actuators	Micro Controller

Table 1: Comparison of exoskeletons for gait assistance

IV. FUTURE TRENDS

The future of assistive exoskeletons is bright and such devices are widely predicted to be in high demand to meet the needs of the global ageing society. Also as many commercial undertakings are emerging to develop commercially viable solutions it is foreseen that elderly people will have access to affordable exoskeleton devices for ensuring that they are able to move around independently and maintain good quality of life in their own homes for as long as possible.. Avoiding high cost sophisticated components like harmonic drives, microcontrollers, and high end DC motors and looking into ergonomic mechanical innovations can help improve the quality of the exoskeletons delivered to the markets. Therefore it is concluded that if proper emphasis is laid on these issues, the exoskeleton market can be developed to reach the masses to provide the needed assistive devices. Moreover, with reduction in cost the demand of exoskeletons will increase not only in developed countries but in developing countries and regions such as India, China and Africa.

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