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Lower Extremity Exoskeleton: Review and Challenges Surrounding the Technology and its Role in Rehabilitation of Lower Limbs

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Abstract: With the advancement in the area of robotics, exoskeleton technology has come a long way since its beginnings in the late 60's. Researchers over the world have developed their own exoskeleton prototypes, and some of the well known exoskeleton includes the BLEEX, MIT exoskeleton, HAL, LOPES, ALEX, and many more. Although technologies have advanced since the 60's, challenges still exist in exoskeleton design. This paper reviews different exoskeleton technologies as well as its role in the area of rehabilitation. This purpose in rehabilitation is promising, based on countless of researches which have been carried out.

Key words: Exoskeleton, Rehabilitation, Lower Limbs, Wearable Robots and Lower Extremity Exoskeleton

INTRODUCTION

Exoskeleton is nothing new, in which it has been given attention by researchers since four decades ago, during the late 1960s (Dollar *et al.*, 2008). In biological terms, an exoskeleton refers to the tough outer covering of an insect which provides support and protection (Guizzo *et al.*, 2005). However, the types of exoskeleton that are referred in this paper are wearable robots intended for human use. These devices, which is electromechanical in nature are able to augment or enhance the physical capability of the human wearer, whether an able-bodied or a physically impaired person (Gams *et al.*, 2013).

In enhancing the ability of an able-bodied person, it is done mainly for military purposes, where the physical strength of soldiers is to be increased. On the other hand, the usage of exoskeletons for the physically handicapped that aims to restore and regain the physical movements of patients. These physical disabilities can be caused by athletic injury, spinal cord injury, or complications due to cerebral vascular accident (stroke) (Murray *et al.*, 2012). For such a usage, patients will benefit tremendously as they will be able to recover at a faster rate, hence allowing them to resume their daily routines prior to the disability. In its usage in the medical field, exoskeletons are referred as active orthèses (Krut *et al.*, 2010).

This review paper focuses exclusively on the lower extremity exoskeleton in its usage for rehabilitative purposes, and its related issues and usage surrounding this particular technology. Discussion also includes some of the design considerations of an exoskeleton in those well known and established projects.

Design of an Exoskeleton:

The design of an exoskeleton is a subject of high complexity, due to different considerations and issues which exist concurrently. In the year 1963, Zaroodny from the U.S. Army Exterior Ballistics Laboratory issues a research paper which deals with his design of an exoskeleton intended for the augmentation of load-carrying abilities in a person (Dollar *et al.*, 2008). Although his design never left the drawing board, he had addressed a few very important issues, namely the problem of power supply, physical interface with the human, sensing and control, and the behavior of the biomechanics of locomotion (Dollar *et al.*, 2008). Besides that, another issue of equal importance is the choice of actuators. Next section reviews the considerations in the design of an exoskeleton, based on well known and established exoskeleton projects.

Actuator:

The earliest known exoskeleton found to date is the "Hardiman" (Human Augmentation Research and Development Investigation), which is a full body exoskeleton jointly developed by researchers from General Electric Research and Cornell University. The exoskeleton is huge, weighing 680kg and has 30 DOFs (degree of freedom) in total. The bulky exoskeleton comes from the fact that it uses hydraulic actuators. In robotic applications, different actuators such as pneumatic, hydraulic, electrical, piezoelectric, electro active polymers, etc. are used. Many of these cannot be used in exoskeleton application, as actuators used in exoskeleton applications are required to provide high torques while operating in high speeds. As a result, selecting the type of actuators is a difficult task as researchers to weigh in the pros and cons of using a particular type of actuator.

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Another exoskeleton project, the Berkeley Exoskeleton (BLEEX) is actuated using linear hydraulic cylinders (Zoss *et al.*, 2006). BLEEX was designed to assist the human operator, while allowing an external payload to be carried. The Sarcos exoskeleton of the Sarcos Research Corporation makes use of its rotary hydraulic actuators to actuate the joints of the device. Other than that, the MIT skeleton was developed by researchers at Massachusetts Institute of Technology Media Laboratory. It is interesting to note that instead of using actuators, they has implemented a quasi-passive design which depends on stored kinetic energy in springs during different phases of the walking movement.

Meanwhile in Japan, an exoskeleton named Hybrid Assistive Limb (HAL) had been developed and made available commercially. Developed and sold by Cyberdyne, it is targeted for rehabilitative purposes and uses unique pneumatic actuators. From this scenario, we can observe that researchers are divided over the use of the type of actuators in their exoskeleton, suggesting that each of these types of actuators comes with their own pros and cons. In the case of the BLEEX, rotary hydraulic actuators were not used as they usually have problem of internal leakage and friction (Zoss *et al.*, 2006).

Human-Exoskeleton Interface:

The human-exoskeleton interface is important for a safe and comfortable interaction with a wearable robotic device (Gams *et al.*, 2013). In term of the physical interface with the human operator, BLEEX was designed in such a way that there is no sensors physically applied to the human, but utilizes sensory information based on force and torque applied to the exoskeleton. The control system obtains data from 16 linear accelerometers, 8 encoders and foot load distribution sensor to determine parameters such as angle, angular velocity, and angular acceleration of the actuated joints (Dollar *et al.*, 2008).

For the Sarcos exoskeleton, it is dependent on force sensors that are physically in contact with the human at particular sections, such as below the feet. These Sarcos-developed sensors send information to the controller's computer which then induces the exoskeleton limbs to move in synchronism with the movement of the user. Meanwhile, the MIT exoskeleton uses all-bridge strain gauges which provides sensory information, and is placed at the exoskeleton shin. Other than that, a potentiometer is also placed at the knee joint for this particular purpose.

The HAL exoskeleton utilizes skin-surface electromyography (EMG) which is placed above knee area and below the hip. In order to measure joint angle, potentiometers are used. While torso posture estimation, ground reaction force sensors, gyroscope, and accelerometer are used. The usage of EMG is advantageous in the application of exoskeleton as it is able to predict the intended motion, even if the limb muscles are too weak to carry out the movement (Fleischer *et al.*, 2006). EMG measurements are prone to high noise disturbances and are dependent on many factors, such as skin conductivity, skin surface excretion, and placement (Gams *et al.*, 2013). Besides that, HAL also utilizes a control system which enables the user and exoskeleton to move together in a synchronized manner, by storing walking patterns; also referred to as gait pattern (Gams *et al.*, 2013).

Mechanical Design:

In the mechanical design of the exoskeleton, different design criteria should be considered. The design criteria as outlined by researchers at the Selcuk University (Onen *et al.*, 2013) includes (1) Ergonomic and comfortable design (2) high maneuverability (3) lightweight and strong structure (4) adaptability to different users and (5) user safety. These are the criteria that they have identified for their lower extremity exoskeleton project Walking Support Exoskeleton (WSE), and indeed these are very important considerations in an exoskeleton.

Addressing point (4), an exoskeleton needs to be adaptable to different users of different body shapes and characteristics. The limbs of every person vary considerably, so the exoskeleton needs to have a feature which enables the physical exoskeleton to be adjusted accordingly. In reference to this, an individual using HAL will need 2 months so that the exoskeleton can be calibrated optimally to suit the user's needs. Referring to point (3), the exoskeleton has to be made strong, in order to be able to handle the weight exerted by the exoskeleton and power supply itself, and also the payload that the user carries. One of the examples is the autonomous BLEEX. It has onboard power supply attached and it is able to carry its own weight and external payload.

In wearing the HAL, a healthy adult will be capable of carrying a load of up to 80kg, justifying the need of a mechanically-strong exoskeleton (Guizzo *et al.*, 2005). Considering the importance of user safety of point (5), there is currently no safety standard for human-robot interaction made available yet. To ensure the standard is met, redundant safety mechanisms must be implemented. Examples of such mechanism are such as limiting the power output, limiting velocities of joint actuators and back-drivable system to reduce motor inertia (Dellon *et al.*, 2007).

Power Supply:

Power supply is being one of the most limiting factor but of great importance in the exoskeleton design. Without an on-board power supply for the exoskeleton, it would be limited only to indoor application 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 bickel-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.

Energy Expenditure:

There have been many studies on the effect of energy expenditure of an exoskeleton. Andrej Gams *et al.* (2013) at Joˇzef Stefan Institute has investigated whether the knee-exoskeleton will reduce the metabolic cost and its influence of using the appropriate control system. In this study, the researchers analyzed this effect by measuring oxygen consumption, minute ventilation, heart rate, blood oxygenation and muscle EMG during five minutes squatting series, at one squat every two seconds, of the volunteer subjects. During this study, the type of control method was varied, to find out the most appropriate type of control method. Regardless of the type of methods, it was shown that the metabolic cost of a periodic task can be reduced significantly (Gams *et al.*, 2013).

However, in a non-periodic task such as walking, an operator with exoskeleton uses up more oxygen than the operator without the exoskeleton (Kim *et al.*, 2010). In another research, it was shown that a reduction of in muscle effort when walking with the exoskeleton, compared to one without exoskeleton. The experiment was conducted on two healthy subjects, using assistive control on ALEX II (Gams *et al.*, 2013) and a treadmill based lower-limb exoskeleton developed at the University of Delaware (Lenzi *et al.*, 2012). This is a two-step controller which the user's joint torque is estimated online and the user's joint with a constant fraction of the torque is estimated using the powered exoskeleton. The basis behind the idea that when assistive torque is supplied, humans will adjust the body's muscle activation in a way the summation of muscular and assistive torque equals the total torque profile along the gait cycle (Kao *et al.*, 2010). The results showed that such a controller is capable of reducing the walking effort in test subjects by as much as 36.5%.

Rehabilitation:

This section focuses the purpose of rehabilitation. Rehabilitation exoskeletons can lessen the strain on physical therapists of stroke survivors, as it offers greater repeatability and quantitative measures of improvements (Banala *et al.*, 2009). The researchers at Vanderbilt University, Nashville conducted a study of usage of lower limb exoskeleton intended for locomotion assistance in individuals with neuromuscular deficits (Murray *et al.*, 2012). Neuromuscular impairments include multiple sclerosis (MS), spinal cord injury (SCI), cerebral palsy (CP) and stroke which result muscle impairments and deficits in gait performance in patients. Researches aim to assist individuals with such impairment using Vanderbilt exoskeleton. Firstly, they proposed that in an exoskeleton system, the detection of the gait phase must be done accurately and correctly, so that the exoskeleton can assist the user in corresponding suitable manner. It is translated in what they called the gait detection (GPD) component of the system. Secondly, the lower limb exoskeleton must not impair natural gait of user "get in the way" of their intended gait movement. This is implemented through active compensation for passive dynamics (ACPD). Passive dynamics here is imposed by the exoskeleton on the wearer through three effects, namely the (1) force exerted on the use due to the mass of the exoskeleton, (2) rotational inertia acted on the joints, and (3) introduction of friction on each of the joints. The results showed that the application ACPD controller enables the user to perform walking in exoskeleton without significantly affecting the user's natural gait movement.

In the design of an exoskeleton for rehabilitation purposes, user acceptance considerations, as well as analysis of limb sensitivity and comfort are vital issues that required to be accounted for. In a human-robot interface, a proper exoskeleton design will ensure that comfort is present for the user. Here, biomechanical interaction is defined by the total interaction between compliant, soft body tissues as well as the support surface through which assistive forces are transmitted (Moreno *et al.*, 2005). The level of comfort is determined by factors such as pressure and shear forces. The author analyzed the sensitivity of lower limb in order to investigate the proper areas to apply external loading and the maximum loads that can be applied without causing pain or discomfort to the user who are wearing the exoskeleton. Through this analysis, exoskeleton interface with certain section of the limb can be avoided, thus increasing comfort of the user. Reduction of shear force reduced trauma to the affected area, which is caused due to repetitive combination of pressure and shear to contact area (Goonetilleke *et al.*, 1999).

Having reviewed the different types of sensing and control of exoskeleton in the earlier section of this paper, there are a variety of methods that are used by researchers in different exoskeleton projects. However, a group of researchers (Yin *et al.*, 2012) seems to agree that EMG signals are better than angle and force information, simply because they can mirror the intended movement in advance and imply muscle activity information, such as speed and contraction strength of a muscle. In saying this, it is no wonder that HAL, which is mainly used for rehabilitative purpose, uses EMG signal sensing as well.

On the other hand, the disadvantage of EMG signals in general is that it contains a large amount of fuzziness. It means that for a person who performs the same motion at different moment, EMG signal will be different. The changes can be brought about by sweat excretion at the sensor placement site, muscle fatigue, changes in level of muscle force production, as well as movement of electrode sensor in relation to its initial placement (Yin *et al.*, 2012). In solving this issue, different algorithms have been applied, such as the Adaptive Neuro-Fuzzy inference system (ANFIS) (Lauer *et al.*, 2005), which is capable of predicting the seven phases of gait cycle with a high degree of accuracy and repeatability, invariant of the level of motor impairment. Other algorithms include the fuzzy C-means clustering algorithm (Momen *et al.*, 2007), and another robust method highlighted by Panagiotis K. Artemiadis *et al*. (2010).

In assessing the effect of using exoskeletons in rehabilitation, researchers from the University of Delaware, Newark performed robot assisted gait training (RAGT) of stroke survivors using the Active Leg Exoskeleton (ALEX) (Banala *et al.*, 2009). Gait refers to the manner a human walks with his limbs. It should be understood that stroke survivors suffer from abnormal gait patterns and this study aimed to restore the gait pattern of stroke survivors to be a normal person. In this study, two stroke survivors underwent a 15-session gait training session. Improvements can be observed after the duration of the training. Improvements were shown through an increase in their treadmill walking speeds. Subject 1 showed walking speed of 1.0mph during the first training and 1.6mph at the end of training, while subject 2 had a walking speed of 1.4mph during the first session and gradually improved to 1.9mph at the end of training.

Meanwhile, another exoskeleton research had been carried out at University of Delaware (Agrawal *et al.*, 2007), which aimed to build a gravity balancing exoskeleton (GBO). In this design, no motors are used and the human joint is made to be free from gravitational load over its range of motion. Gravity balancing is achieved through intelligent use of counter weights (Dresig *et al.*, 2011), thus reducing the power output of actuators during motion. The principle behind such method is that the sum of inertial forces and moments of the mechanisms and the balancing body is nil, where the desired motion of the balancing body can be calculated. From the analysis of obtained results, the researchers concluded that gravity assistance increases the range of motions of leg joints. It can be observed on healthy and stroke impaired test subjects. In the case for stroke test subjects, there is a significant increase of almost 50% of range of motion at the hip and knee. The study was conducted in such a way that the stroke patient underwent a six-week training study using the GBO, where gravity assistance was subsequently reduced from 100% to 0% at timed intervals. It can be observed that GBO promotes gait improvement, and there was also increase in walking speed and weight bearing of subject. Besides that, the subject had a more symmetric walking pattern.

Conclusion:

Exoskeleton technology, although proven to be beneficial and advantageous in the area rehabilitation of patients, still has its own challenges that need to be addressed. This paper has reviewed different exoskeleton technologies, as well as the basis of using a particular type of technology for the exoskeleton design. The challenges surrounding exoskeleton technology such as selection of actuators, power supply consideration, mechanical design, human-exoskeleton interface and control method still need to be improved upon. Through exoskeleton technology, we have seen its application in the medical field, where it is used in the rehabilitation of patients who are physically impaired due to neuromuscular diseases and complication.

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