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A STUDY ON THE STATE OF POWERED-EXOSKELETON DESIGN FOR LOWER EXTREMITIES

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ABSTRACT
In this paper, previous works in powered exoskeleton are studied and their contributions in the field of robotics technology are highlighted. This paper will also address issues that were encountered in each project and the solutions made to resolve the problem. Future directions in work related with the design of an efficient, low-mass exoskeletons and the study of some safety issues will also be discussed.

Key Words – Exoskeleton, lower extremities, gait analysis

I. INTRODUCTION

Research in powered human exoskeleton devices began in the late 1960s by two countries – United States and Yugoslavia. United States was primarily focused on developing exoskeleton in strenghtening the person's abilities, while Yugoslavia focused more on developing assistive exoskeletons in assisting physically challenged persons especially during their rehabilitation [1]-[2].

Exoskeletons are suits or wearable devices that is placed around the human body. Lower extremity exoskeletons can be used for different purposes – performance amplification, locomotion (ambulatory), and rehabilitation [3]. An exoskeleton providing performance amplification is typically used to increase the strength and endurance of the user. This type of exoskeleton is very useful for the military especially in in carrying weapons and providing relief with ease. In the other hand, exoskeletons for ambulatory and rehabilitation assist patients to walk by providing joint trajectories of the gait cycle.

In general, the word exoskeleton is used to describe a device that is designed to assist, protect and augments the performance of the pilot or wearer.

II. EXOSKELETON DEVELOPMENTS

2.1. Early Exoskeletons

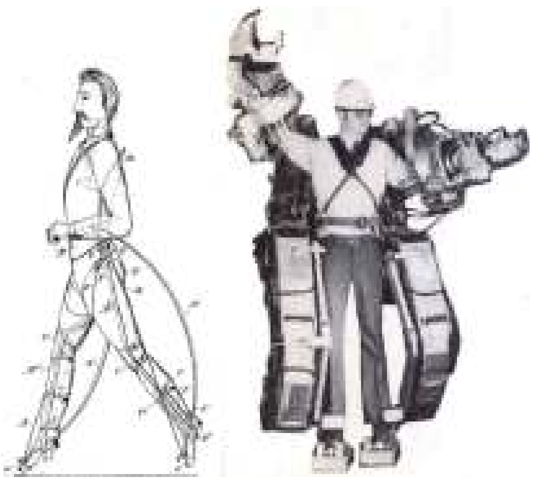
The first exoskeleton project started with the idea of Yagn granting him with two US patents. In 1890, he made a concept in making a robotic apparatus that will aid people in walking, running, and even in jumping [4]. His model of a lower extremity enhancer consists of a long bow operating in parallel to the legs of the user. Even his proposal was designed to augment running, the device was never built.

Major exoskeleton projects in the US were really designed for military purposes. In 1963, Zaroodny [5] of the U.S. Army published a paper on making a simple device that would assist a person in walking. In his report, he already identified issues in the implementation of the device like portable power supply, sensors, controls, human-machine interfacing, and the biomechanics of locomotion. He concluded after some informal evaluation the use of a pneumatically-powered robot for his project. Even his proposal was considered to be the earliest publication in addressing complications of a powered-exoskeleton, he never had a chance to secure some funding to continue the project.

In 1960s, General Electric Research, in collaboration with Cornell University and the US Office of Naval Research Institute, developed a full-body powered exoskeleton prototype that they named Hardiman. This hydraulically powered machine, having 30-DOFs, was impractical due to its 1,500 pounds (680 kg.) weight. The main objective of the Hardiman project is to amplify the strength of its wearer by

25 times. Unfortunately, the project turned out not to be successful. The robot was simply too large and bulky to maneuver easily. Though the implementation is unsuccessful, still, the project was able to attempt in providing a good solution for the issue in portable power supply and human-machine interface [6]-[9].

Fig. 1. Yagn's model [4], GE's Hardiman [6]



Works on lower limb exoskeleton for the military continue to flourish until Jeffrey Moore, an engineer of Los Alamos National Laboratory, proposed his project called Pitman [10], a powered suit of armor for soldiers. For the robot's control system, he employed a network of brain-scanning sensors in the helmet that will measure the magnetic fields generated by the brain. In contrast with Hardiman, Pitman did not address how problems such as power supply and implementation were going to be solved. Even his idea had never been a success due to lack of funds from the US Defense Department, it gave way to the U.S. Defense Advanced Research Projects Agency (DARPA) exoskeleton program.

Another researcher named Mark Rosheim, who coined the word 'anthrobotics', expanded the idea of Hardiman and Pitman in his paper by incorporating singularity-free pitch–yaw type joints in order to present a full-body, 26 DOF exoskeleton concept [11].

2.2. DARPA Exoskeletons

In 2000, the US Defense Department funded the project Berkeley Lower Extremity Exoskeleton or BLEEX in providing human especially soldiers the ability to carry major loads like food supply, rescue equipment, first-aids, and weaponry having minimal effort for extended periods of time. The idea of BLEEX really came from Kazerooni [13] of the University of California Berkeley's Human Engineering and Robotics Laboratory. Together with Steger, they were able to demonstrate successfully the first experimental exoskeleton in which the pilot could carry a heavy load, while feeling only a few-pound load. Because of this development, they were able to claim BLEEX as the first functional load-carrying and energetically autonomous exoskeleton [14].

The primary objective of the BLEEX project is to produce an autonomous exoskeleton that will aid in amplifying and enhancing both strength and endurance of humans. The project also try to address and solve problems in ergonomics, maneuverability, robustness, weight factor and durability of lower-limb exoskeletons [15].

The first experimental prototype BLEEX is composed of two powered anthropomorphic legs, a power unit, and a backpack-like frame, as seen in Figure 2. To answer problems in power supply, BLEEX uses a state-of-the-art small hybrid power source which is capable of delivering a large hydraulic power for locomotion. Not only in terms of power supply performance, BLEEX was also able to address issues in robustness and reliability by designing a system capable under extreme operating conditions and environment. After a series of experimentation, the researchers were able to conclude and identify problems in mobility requirements like payload specifications, terrain and speed parameters [16]-[17].

In terms of usage performance, with BLEEX, the wearer can easily support a load of up to 75 kg while walking at 0.9 m/s, and can walk at speeds of up to 1.3 m/s without the load. As of now, a second generation of the BLEEX robot is currently develop and undergoing several test. This new BLEEX, as compared with its predecessor, is approximately half the weight [18]. This is due to the implementation of an electric actuation instead of an hydraulic transmission system.

Another DARPA funded-exoskeleton program similar to BLEEX is the Sarcos Exoskeleton project developed by the Sarcos Research Corporation in Salt, Lake City, University of Utah. The Sarcos Research Corporation had been well-known as a research and development leader in building advanced robotic systems both in military and industry, as well as designing medical devices like artificial limbs and vascular systems.

Project Sarcos started to develop exoskeletons for the United States Army in 2008. The Sarcos design involves a suit that is engine-powered with a tank holding 24 hours of fuel, which is found near the wearer's buttocks. In similar to BLEEX, Sarcos was designed not only to increases the strength of the wearer but also its endurance because of the engine that is used to run servo motors [19].

Sarcos had become popular in making great advancements in the concept of producing hydraulically actuated exoskeleton. According to Dollar (2008), “Although Sarcos has not reported the power requirements of their exoskeleton, they have spent a significant amount of effort developing power supplies and servo–valves for efficient hydraulic actuation of the exoskeleton” [32].

After the DARPA program ended, the Sarcos project was able to continue in developing exoskeleton after securing a large amount of additional fund from a private sector. In November 2007, Raytheon purchased Sarcos for an undisclosed sum, seeking to expand into robotics research and production. Last September 2010, Raytheon was able to launch its second-generation exoskeleton which is XOS2. Essentially, XOS2 is a wearable robotics suit developed for the military people. It is lighter, stronger and faster than its predecessor XOS, but using only 50 percent less power. It is built from a combination of structures, sensors, actuators & controllers, and powered by high pressure hydraulics.

The Biomechanics Group of the Massachusetts Institute of Technology developed a quasi-passive exoskeleton concept. The objective of this project is to exploit the passive dynamics of human walking in order to produce an efficient exoskeleton but lighter in weight. To employ this idea, their design did not use any actuators for adding power at the joints. Instead, the design relies completely on the controlled release of energy in the springs [21]-[23]. They were able to determine based on the kinetics and kinematics of walking, the springs and variable dampers as quasi-passive elements.

Walsh (2006) claimed that their results showed significant reduction in metabolic cost of walking versus an exoskeleton, having no quasi-passive elements, by ten percent (10%).

Fig.2. BLEEX [18] (image credit to Prof H. Kazerooni). MIT Exoskeleton [21]

2.3 Assistive Exoskeletons

A group of researchers in the University of Tsukuba developed an exoskeleton concept to address both performance augmentation and rehabilitative purposes. They dubbed the exoskeleton Hybrid-Assistive Leg (HAL-5) [25], which is a full-body battery-powered suit designed to aid elderly and disable people. The leg structure of HAL-5 exoskeleton powers the flexion and extension joints at the hip and knee using a dc motor. A main challenge is to detect the motion intention of the user. To accomplish this, nerve signals that flow along muscle fibers should be measured which are generally sensed with electromyograms (EMGs). Then, a control unit determines the required assistive power and commands the actuators to produce a specific torque.

The Nurse-Assisting Exoskeleton [27], another project in Japan by a group of researchers from Kanagawa Institute of Technology, helps in assisting nurses during patient transfer. The lower limb components include direct-drive pneumatic rotary actuators for the flexion and extension of the hips and knees. Air pressure is supplied from small air pumps mounted directly to each actuator, allowing the suit to be fully portable.

User intent is determined via muscle hardness sensors created by attaching force sensing resistors (FSR) to the skin surface above a muscle via an elastic band. As the knee is flexed and the muscle is contracted, FSR increases, which, along with the joint angle information from potentiometers, is used to determine the torque required at the joint [28].

One of the interesting aspects of the mechanical design of the Kanagawa full-bodied suit is that there is no mechanical component on the front of the wearer, allowing the nurse to have direct physical contact with the patient that he or she is carrying. This is an important property for ensuring the comfort and security of the patient.

RoboKnee [29] is a simple exoskeleton, consisting only of one (1) degree of freedom. The robot is designed to assist its wearer in climbing stairs and performing deep knee bends. The device is only consists of a linear series elastic actuator connected to the upper and lower portions of a knee brace.

RoboKnee clearly demonstrated a simple control algorithm in providing performance augmentation to the wearer. However, the bulkiness and the battery recharging problem are still issues of the RoboKnee. Problems like these can be addressed by using more compact actuators and better energy resources.

In 2005, another assistive-exoskeleton named LOwer-extremity Powered ExoSkeleton (LOPES), published by Ekkelenkamp et al. [30], was developed for assisting physically challenged persons. The main objective of the LOPES project is to implement a gait rehabilitation robot on treadmills for stroke patients. Great about this robot is that it can perform in two different modes -a 'patient-in-charge' and 'robot-in-charge' mode. The first mode works when the patient tries to walk freely without the help of the robot while the second mode applies when the robot is the one controlling the patient especially if he or she is unable to perform [31].

Fig. 3. HAL-5 [26]. Nurse-Assisting Exoskeleton [27]. RoboKnee [29] (images are under Creative Commons Attribution)

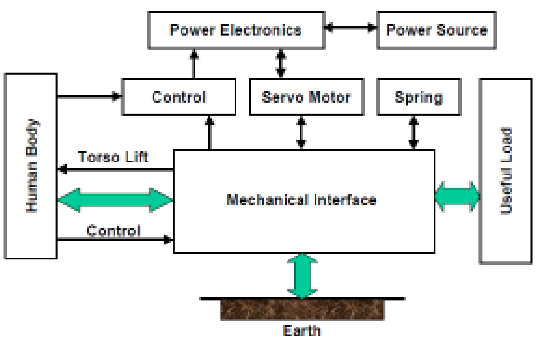
III. FUTURE DIRECTIONS AND CHALLENGES

Most of the work related to the development of exoskeletons will likely focus around the following technological issues such as power supply, controls, actuation system, and transmissions. Providing solutions to these problems will help in developing a very efficient but having low-mass exoskeletons. Recent advancements in sensor, actuator, and microprocessor technologies could bring about future exoskeletons, like the one use in ambulatory, that do not require the use of the external balancing aids.

Beside the challenges in the technologies, there are still few issues related to the implementation of exoskeletons that have been largely ignored. One is the study on the safety of the human operator or pilot, who is inside controlling the robot [32]. Based on Haptic Cobot Exoskeleton, human safety relies on three factors; mechanical design, actuation and control. This type of robot provides a significant improvement in existing haptic exoskeleton technology by providing high performance haptic feedback while maximizing the user's safety [33].

For the exoskeleton mechanical design, mechanical interface is always been a part of all exoskeleton designs. As shown in Fig. 3, it is the one that couples the device to the user's feet in order to provide absolute feedback and allows user input into gait. From Dick's design [34] of servo-assisted lower limb exoskeleton, different interfaces have been studied. These interfaces are the parallel interface that adds force, series interface for the motion and leveraged leg interface that adds both the force and the motion.

Fig. 4. Exoskeleton Subsystem [34]



For an exoskeleton, the cooperation between the user and the robot is designed in such a way that the human is in control of the movements. But in reality, exoskeletons do not always have to work in cooperation with the operator: Instead, they offer a unique way of giving force feedback to the human body. The work of Fleischer [35] presented a control system for exoskeletons that utilizes electrical signals from the muscles as the main means of information transportation between the human operator and the exoskeleton. Electrical signals are picked up from the skin on top of selected muscles and reflect the activation of the observed muscle. They are evaluated by a sophisticated but simplified biomechanical model of the human body to derive the desired action of the operator.

Physical requirements like muscle and tendon function used for walking comprises the mechanical design of an exoskeleton. There have been gait analysis models, like in BLEEX [14], that ensure sufficient kinematic flexibility to allow natural dynamic movement.

For the actuation, there already had been various actuators used in safety-critical applications. Designers of this safety-critical control applications face several problems in meeting safety requirements especially in strategizing safety analysis, engineering design and lifecycle application guidelines.

Previous work on exoskeleton design has not considered the passive dynamics of walking and has focused on fully actuated systems that are inefficient and heavy. Walsh [20] designed an under-actuated exoskeleton that runs parallel to the human leg which is based on the kinematics and kinetics of human walking. His work greatly reduces the stress on the shoulders and back. However, the exoskeleton is found to have an increase in metabolic economy. Designing a lighter and more efficient actuator that requires a small power supply will reslove the issue on metabolic rate.

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