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Abstract

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ABSTRACT

This literature review of exoskeleton design provides a brief history of exoskeleton development, discusses current research of exoskeletons with respect to the innate human-machine interface, and the incorporation of exoskeletons for ergonomic intervention, and offers a review of needed future work. Development of assistive exoskeletons began in the 1960's but older designs lacked design for human factors and ergonomics and had low power energy density and power to weight ratios. Advancements in technology have spurred a broad spectrum of research aimed at enhancing human performance and assisting in rehabilitation. The review underwent a holistic and extensive search and provides a reflective snapshot of the state of the art in exoskeleton design as it pertains to the incorporation of exoskeletons for ergonomic intervention. Some of the remaining challenges include improving the energy density of exoskeleton power supplies, improving the power to weight ratio of actuation devices, improving the mechanical human-machine interface, and dealing with variability between users.

KEYWORDS

Assistive Technologies, Biomechanics, Exoskeletons, Human-Machine Interface, Human-Robot Interaction, Physical Ergonomics

1. INTRODUCTION

The field of exoskeleton design is broad and expansive. This paper serves as a cogent literature review of exoskeleton design with respect to the human-machine interface. It provides an outline of a brief history, current research, the potential benefits of exoskeleton use, and finishes with a discussion of the possible future of exoskeletons.

It is imperative to begin this paper by clearly defining the difference between exoskeletons and orthotics. It is also important to note that these two terms often overlap in the media as well as in the scientific literature.

An exoskeleton can be identified as an external mechanical structure whose joints matches those of the human body. This mechanical structure shares physical contact with the operator and enables a direct transfer of mechanical power and information signals through either passive or active actuation (Pons, Rocon, & Morenso, 2007).

An orthotic, or orthosis (plural: orthoses) refers to a device that is externally applied to the body. It is different from a prosthetic where a device substitutes a missing body part. External devices, such as dental braces, insoles, or a pair of glasses are examples of orthotic devices (Sarakoglou, Tsagarakis, & Caldwell, 2004). Active orthoses are limited by the daunting issue that the specific

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nature of disability varies from one person to another. This makes it difficult to create one generally applicable device. Ideally, a compact, energetically autonomous orthosis can provide the wearer assistance and therapy in everyday life. The issue of portability is one of the major factors that limits the application of active orthoses outside of clinical therapy (Dollar & Herr, 2008).

Hugh Herr defines exoskeletons and orthoses as follows: "The term 'exoskeleton' is used to describe a device that augments the performance of an able-bodied wearer, whereas the term 'orthosis' is typically used to describe a device that is used to assist a person with a limb pathology (Herr, 2009)."

Initial development of exoskeletons can be traced back to the early 1960's with the US Defense Department's interest in the development of a man-amplifier. A man-amplifier was a "powered suit of armor" which could augment a soldier's lifting and carrying capabilities (Kazerooni, Steger, & Huang, 2006).

General Electric (GE) developed the first exoskeleton device, beginning in the 1960's and continuing until 1971, called the Hardiman. It was developed by Ralph Mosher, an engineer for GE. The suit made carrying 250 pounds seem like 10 pounds. It was a hydraulic and electrical body suit. The outer body suit followed the motions of the inner body suit in a master-slave system. It was determined to be too heavy and bulky for military use. The general idea was well received, but the Hardiman had practical difficulties due to its own weight of 1500 pounds. The walking speed of 2.5ft/sec limited its uses. Any attempted practical testing with the exoskeleton was impossible with a human inside due to the uncontrolled violent movements (Ali, 2014).

In 1962, the US Air Force commissioned the study of a master-slave robotic system for use as a man-amplifier from the Cornell Aeronautical Laboratory. Through their study, the Cornell Aeronautical laboratory found that an exoskeleton, even one with fewer degrees of freedom (DoF) than the human body, could accomplish most desired tasks (Mizen, 1965). However, the master-slave system that the man-amplifiers used were deemed impractical, had difficulty in human sensing, and were overly complex, making walking and other tasks difficult to complete (Kazerooni, Steger, Huang, 2006).

Exoskeleton research and design continued. The University of Belgrade, located in Serbia, developed several designs throughout the 1960's and 1970's to aid paraplegics. These exoskeletons were limited to predefined motion with limited success. The balancing algorithms developed for these exoskeletons are still used in many bipedal robots (Vukobratovic, Ciric, & Hristic, 1972).

2. OVERVIEW OF EXOSKELETONS

2.1. Uses and Market

Exoskeletons are used in two primary roles: rehabilitation and human performance augmentation. However, their use is quickly expanding into other fields such as sports, firefighting, and law enforcement. According to Rocon (Rocon et. al., 2007) and Harwin (Harwin et.al., 1998), rehabilitation robotics, and by extension rehabilitation exoskeletons, can be classified into three categories:

1. Posture support mechanisms
2. Rehabilitation mechanisms
3. Robots [and exoskeletons] to assist or replace body functions

The goal of human performance augmentation (HPA) is to enhance the capabilities of otherwise healthy people. Applications include fatigue reduction and heavy lifting, with much research focused on military uses, such as enhancing the ability to carry large loads onto the battlefield and increasing the endurance of the soldier. Other possible markets for HPA include emergency services such as fire and disaster response, and construction and material handling (Brown, Tsagarakis, & Caldwell, 2003), or any application that requires heavy gear and heavy lifting in rough terrain impassable by vehicle.

This paper divides exoskeletons into four broad categories of lower body, upper body, hands/feet, and full body exoskeletons.

2.2. Lower Body Exoskeletons

Lower body exoskeletons are mainly comprised of the hip joint, the knee joint, and the ankle joint. Among different challenges involved in developing an exoskeleton for the lower body are the interface between the human and the exoskeleton, portable energy sources, controls, and actuators. Lower body exoskeletons can be broadly divided into two types based on the application: rehabilitation, as well as enhancement capabilities of a healthy human being.

Most lower body exoskeleton robots first started to assist soldiers in supporting equipment. Wearable lower suits can greatly reduce the oxygen consumption of soldiers; support energy for walking, running, and jumping; and help movement and operational capability of soldiers (Yuan et. al., 2014). Therefore, the exoskeleton robot, also called a wearable robot, is a mechanical robot that humans can wear (Dollar & Herr, 2008). It is important to understand the biomechanics of humans in order to develop ergonomic designs of exoskeletons and active orthoses for the lower limbs (Dollar & Herr, 2008).

2.2.1. BLEEX

The Berkeley Lower Extremity Exoskeleton, or BLEEX, is the first energetically autonomous robotic exoskeleton that was successfully demonstrated to provide an operator with the ability to carry significant loads with minimal effort over any type of terrain. BLEEX has four critical features: (1) a novel control scheme, (2) high-powered compact power supplies – hydraulic and electric actuations that have been designed to power BLEEX, (3) a special communication protocol and electronics, and (4) a design architecture that decreases complexity and power consumption (Chu, Kazerooni, & Zoss, 2005; Zoss, Kazerooni, & Chu, 2006).

The BLEEX enables its wearer to carry a heavy load. It was first presented from U.C. Berkeley's Human Engineering and Robotics Laboratory supported by the Defense Advance Research Project Agency (DARPA) (Dollar & Herr, 2008). The BLEEX seeks to supplement the intelligence and sensory systems of a human with the significant strength and endurance of a pair of wearable robotic legs that offers a payload capacity (Chu, Kazerooni, & Zoss, 2005).

2.2.2. HAL-5

HAL-5, the fifth rendition of the Hybrid Assistive Limb (HAL), is a powered exoskeleton suit which now include upper-body limbs, lighter and more compact power units, longer battery life, and a better body shape to fit humans more easily and ergonomically. This suit also includes two control systems—voluntary control and autonomous control (Guizzo & Goldstein, 2005). HAL-5 is designed to not only help disabled patients in hospitals and the elderly, but also to support workers with demanding physical jobs, such as disaster rescue or construction (Guizzo & Goldstein, 2005).

2.2.3. XOS2

Sarcos, an engineering and robotics firm, first developed the XOS2, a second-generation robotics suit, in 2006 after receiving a grant from DARPA. Sarcos was purchased by Raytheon in 2007. The wearable suit enables the user to enhance human strength, agility, support a soldier's capabilities for movement with power, and lift heavy objects (Raytheon, 2014). The XOS2 has the capability of weight loading on one foot by using powered limbs. Although dynamic functions of the suit have been developed, an energy problem with the suit has not yet been resolved. It is limited due to a low capacity battery (Yuan et. al., 2014).

The XOS2 is a whole-body exoskeleton, larger than a human's body, but does not entirely imitate the shape of humans (Yuan et. al., 2014). The human body, using an XOS2, receives output from exoskeleton's sensors to minimize the assistance a soldier wearing it can receive, with less effort required to carry heavier loads because the exoskeleton supports the load providing less stress on the human frame (Yuan et. al., 2014).

2.2.4. ReWalk

The ReWalk (Argo Medical Technologies Ltd.) is a wearable robotic exoskeleton which supports powered hip and knee motion to enable individuals with a spinal cord injury (SCI) to stand upright and walk (ReWalk, 2014). The system of ReWalk allows independent, controlled walking and standing while simulating the natural gait patterns of the legs (Zelig et. al., 2012). Although these devices have significant potential physiological benefits, they still have not attained proficiency to be a functional daily use device. Like many exoskeletons today, one of the major issues is the high-energy demands imposed that functional use of the commercially available ambulation devices for paraplegics requires.

2.2.5. Soft Exosuit

Developed by the Wyss Institute, the Soft Exosuit consists of a combination of sensors, such as a hyperelastic strain sensor and sensors around the wearer's hips, calves, and ankles secured by straps (Soft Exosuit, 2014). The soft flexible materials, composed of "soft, functional textiles woven into a piece of smart clothing" (Soft Exosuit, 2014), not only interface with the wearer, but also provide a flexible structure so assistive torques can be applied to biological joints (Soft Exosuit, 2014). This soft exosuit has strong commercial potential for helping spinal-cord injury patients walk or helping soldiers carry heavy loads (Soft Exosuit, 2014). The main benefit of the Soft Exosuit is its extremely light design due to the soft material. The wearer's bone structure must sustain all the compressive forces normally encountered by the body plus the forces generated by the body (Asbeck et. al., 2013). Therefore, the Soft Exosuit, as a potential tool, can help physical workers with hard tasks and support gait, and also assist in rehabilitation and protection from injury, including spinal cord impairment from heavy physical activity (Asbeck et al., 2013).

The overall challenges of lower exoskeleton robots are to (1) have lightweight actuation and efficient transmission; (2) maintain power, actuation, and other subsystems, (off the shelf components do not meet the low weight, high efficiency, and other criteria needed to accomplish their design objective); and (3) examine quantitative performance results for exoskeleton devices that reportedly improve human locomotion.

To achieve the above challenges, lower exoskeleton robots should develop computing, sensing, and control without pervasive application. Therefore, matching the structure of the exoskeleton to the wearer is a fundamental factor. Four criteria must be considered and met, including the need for (1) alignment between joints of the robot and the wearer; (2) segment running and/or jumping ability; (3) safety of the human operator; and (4) a naturally interfacing exoskeleton or active orthoses with the human body.

2.2.6. The RoboKnee

Focused on low impedance, the RoboKnee (a prototype exoskeleton), presents low impedance to the wearer and has a natural interface. To achieve transparency between human and machine, the exoskeleton must successfully perform the following functions:

- Determine the user's intent
- Apply forces when and where appropriate
- Present low impedance

User intent is determined through the knee joint angle and ground reaction forces (Pons et al., 2007).

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 (Pratt, Krupp, & Morse, 2014).

Due to low energy density batteries, the RoboKnee does not yet achieve a long life requirement. While it is very comfortable to use, the current implementation is somewhat difficult to don and doff. While the RoboKnee enhances strength and endurance, it was not designed for enhancing the user's speed and in fact, restricts the user from running (Pratt, Krupp, & Morse, 2014). Further recommendation from authors was to develop an exoskeleton that incorporates other joints than just the knee (Pratt, Krupp, & Morse, 2014).

2.3. Upper Body Exoskeletons

Development of upper body exoskeletons presents additional challenges beyond those of lower body devices. These challenges owe largely to the purpose of upper versus lower limbs. Whereas the purpose of the lower limbs is largely to bear and transport the load of the upper body, "the main function of the arm is to position the hand for functional activities (Rocon et al., 2007)." Furthermore, upper limb joint anatomy is complex. The shoulder, for example, is located by three bones (the clavicle, scapula, and humerus), and allows four articulations, resulting in a dynamic and irregular center of rotation (Gopura & Kiguchi, 2009) making efficient and ergonomic designs difficult, complex, and expensive to make.

Much of the research in upper body exoskeletons has been focused in the medical field, on exoskeletons that provide rehabilitative training or assistance in the daily activities of living. However, upper body exoskeletons could also be applied to augment the performance of healthy individuals (Brown, Tsagarakis, & Caldwell, 2003), to provide a haptic interface in virtual reality simulations, or to act as a master device in teleoperation (Perry, Rosen, & Burns, 2007). Some specific samples from the literature are described in the following sections.

2.3.1. Posture Support

An important function of upper body exoskeletons has been posture support. The SUEFUL-7 is a 7DoF upper-limb motion assist exoskeleton robot that is used to test electromyography (EMG) control methods using neuro-fuzzy modifiers in assisting the motions of the shoulder, elbow, forearm, and wrist of physically weak individuals. The use of the neuro-fuzzy modifiers allows impedance parameters to be adjusted in real time by considering the upper-limb posture and EMG activity levels (Gopura & Kiguchi, 2009).

The T-WREX or Therapy Wilmington Robotic Exoskeleton, is a 5DoF upper arm exoskeleton containing an orthosis, a grip sensor, and software that is used in the training of stroke patients. WREX, the original design, was developed to assist children in daily living activities who do not have enough strength in their arms. The T-WREX enables a wide reach of the arm across a workspace, hand grip pressure detection, and functional training movement simulation (Sanchez et al., 2006).

The Wearable Orthosis for Tremor Assessment and Suppression (WOTAS) provides a means of testing and validating control strategies for orthotic tremor suppression (Rocon et al., 2007). Unlike most exoskeletons that seek to enhance intended muscle movement, the purpose of WOTAS is to dampen unintended movement, and it is capable of operating in both active and passive damping modes. The control algorithm of WOTAS must distinguish between wanted and unwanted movement.

2.3.2. Rehabilitation

One of the most useful and most researched functions of upper body exoskeletons has been rehabilitation of the body. The Cable-Actuated Dextrous Exoskeleton for Neurorehabilitation (CADEN-7) is an anthropometric 7DoF powered exoskeleton system with negligible backlash, backdriveable transmissions, low-inertia links, high stiffness transmissions, open mechanical human machine interfaces (mHMI's), and a range of motion (ROM) representing 88% of a human physiological ROM (Perry & Rosen, 2006). CADEN-7 was used in the development of myoprocessors for upper limbs based on the Hill phenomenological muscle model. Genetic algorithms were used to optimize the internal parameters of the myoprocessors using an experimental database that provided inputs to the model. Research results indicated high correlation between joint moment predictions of the model and the measured data, suggesting that the myoprocessor was sufficiently robust for further integration into exoskeleton control systems (Perry & Rosen, 2006).

Most upper limb rehabilitation systems have been developed for unilateral training, but the upper limb exoskeleton rehabilitation device (ULERD) can be used for bilateral training. The ULERD has three active DoF and four passive DoF. The ULERD incorporates a commercial haptic device known as Phantom Premium, as well as an inertia sensor known as MTx, to detect input signals from one arm which is held stationary. The output movement is performed by a wearable exoskeleton on the right arm, and also shown graphically using an OpenGL animation (Song & Guo, 2011).

ARMin is used for rehabilitation purpose of the arm, which has 4DoF and 2 passive DoF enabling elbow flexion/extension and shoulder rotations. It was installed with multiple sensors for position, force, and torque, so that this robotic system can combine the cooperation and motivation of patients into therapy activities, and give support to the patients based on their needs. Special mechanical design can be seen in ARMin, which includes a customized module for upper arm rotation, enabling small friction during rotation and patient comfort while wearing the device (Miller et al., 2009). ARMin II, which is a 7DoF robotic system for therapy purposes, was developed after the first version. ARMin II can adapt to different patients' sizes with adjustments of five parts and be optimized for combining user cooperation with control strategies. The ARMin II is under evaluation and testing for further improvements (Mihelj, Nef, & Riener, 2007).

The Cable-driven Arm Exoskeleton (CAREX) is lighter weight compared to a traditional rigid exoskeleton. Cables are used to move human upper body segments, which are powered by motors and guided by cuffs. CAREX can provide push and pull with predefined force in required direction during rehabilitation trainings (Mao & Agrawal, 2012).

The Mirror Image Movement Enabler (MIME) robotic device is the result of development work that has been happening since 1998. Early research indicated that bilateral training was more effective than unilateral training when using similar movements. A robotic controller (PUMA 560) was used to manipulate the forces needed, which therapists use for normal therapy training. The movements assisted by robot can be classified as four different types: passive, active-assisted, active-constrained, and bilateral. During passive training, the robot moves the human arm to reach the target with a defined path without human effort. During active-assisted training, a human initiates the movement using force and collaborates with the robotic device to reach the target. During active-constrained training, desired movements are defined by the robot and the maximum effort of the operator needed to reach the target. During bilateral training, the target arm is assisted by the robot to do the same movement as the contralateral arm. In this study Fugl-Meyer and EMG data were collected and analyzed for rating the improvement of the participants and the muscle engagement during the training (Lum et al., 2006).

Significant research and development of exoskeleton use in medical and rehabilitation fields has been completed. ABLE was developed at CEA-LIST Interactive Robotics Unit, a French public research institute specializing in digital systems design. The first applications were used in a rehabilitation project. Further applications for industry and professional fields include intuitive telerobotics, haptic devices for Virtual Reality (VR), and sports training. ABLE used a circular guide for the shoulder joint, which solved the problem of singularity. ABLE used a screw cable system and could be integrated with the motor power transmission of another robotic without modification. ABLE with 4 axes benefited the rehabilitation project. The ABLE-7 axis model has a lighter weight and a 3-axis open forearm-wrist, which can be used for teleoperation and virtual reality (Garrec et al., 2008).

2.3.3. Human Performance Augmentation

The Titan Arm is a lightweight upper body exoskeleton designed to closely mimic human range of motion and assist weakened individuals with regained mobility and independence. The Titan Arm provides 3DoF with non-localized actuation, and a ratchet based braking system that allows it to hold static loads without requiring force from the user (Beattie et al., 2012). The Titan Arm carries most of its weight in the back-plate and is capable of augmenting the user's lifting strength by up to 40 lbs. In addition, the system is able to provide real-time joint tracking, which can be streamed to a computer for analysis.

2.4. Extremities

For the purpose of this paper, we break down the extremities into two primary sections: the hands and the feet/ankles.

2.4.1. Hands

Much of the literature for hand exoskeletons points towards their use in rehabilitation. However, there has also been work done looking at the use of hand exoskeletons as haptic interfaces for interaction with virtual environments and extravehicular activities in space. Extravehicular activity refers to work done outside of the vehicle.

2.4.2. Rehabilitation

The Hand Exoskeleton Rehabilitation Robot, or HEXORR, is an exoskeleton whose robot joints are aligned with anatomical joints of the human hand and provides direct control of these hand joints. HEXORR uses a low-friction gear train and electric motors. This combination allows for both position and torque control, which is an advantage. Another advantage, which HEXORR provides, is psychologically accurate grasping patterns, which are controlled with just two actuators, compared to other complex designs that use eighteen actuators. All of these factors make HEXORR unique compared to other devices (Schabowksy et al., 2010).

The use of EMG signals to control exoskeletons is becoming more commonplace, especially in paraplegics and quadriplegics (Au, Arthur, & Kirch, 2000; Ito et al., 1992; Kirch & Au, 1997; Kuribayashi et al., 1993). There are over 12,000 new cases of spinal cord injury per year (Foundation for Spinal Cord Injury Prevention Care and Cure, 2014) and "nearly half of these cases result in a loss of sensation or motion to the arms and hands" (Lucas, DiCicco, & Matsuoka, 2004). The researchers at Carnegie Mellon University developed an effective EMG-based hand exoskeleton that enabled pinching movements in patients who lacked hand mobility. It uses a functional electrical stimulation system (a system that stimulates muscles that no longer receive signals from the central nervous system), and a low-profile lightweight exoskeleton that consists of "an aluminum anchoring plate mounted to the back of the hand and three aluminum bands, one for each of the finger bands (Lucas, DiCicco, & Matsuoka, 2004)," in conjunction with steel cabling that runs along the front of each finger band, a pneumatic cylinder, and a mechanical linkage mechanism.

An exoskeleton designed for upper arm rehabilitation and hand grasp training called the IntelliArm is able to control the user's shoulder, elbow, wrist, and finger with 8+2DoF. The IntelliArm builds on the research of the following: MIT MANUS, an upper body arm exoskeleton that assisted in arm reaching movements in post stroke rehabilitation (Hogan et al., 1995; Krebs et al., 1997); Reinkensmeyer et al.'s Arm Guide robot, another upper body arm exoskeleton that was used to treat and evaluate post stroke patients by guiding their arm along a linear guide (Reinkensmeyer, Dewald, & Rymer, 1999); and an industrial robot attached to a forearm splint called MIME, or a mirror image motion enabler, that assisted movement passively or actively (Burgar et al., 2000). The IntelliArm also built on the work of the ARMin, described in section 2.3 Upper Body. The designs of the other rehabilitation robots that the IntelliArm built upon did not consider patients' hand posture. The researchers found that if they were to "ignore a proper control of the muscle tension of a subject's hand, the robotic training may lower hand/finger flexibility and potentially cause an abnormal muscle tone (Ren, Park, & Zhang, 2009)."

A tendon-driven exoskeleton that controls flexion of 2DoF per finger was designed for physical therapy at the University of Salford (Sarakoglou, Tsagarakis, & Caldwell, 2004). A hand exoskeleton for the rehabilitation of stroke patients is the Rutgers Master II, which actuates the user's fingers via four pneumatic pistons located inside the palm (Bouzit et al., 2002).

Another hand exoskeleton designed for stroke patients is the Wrist/Finger Force Sensing module (WFFS), which is used during movements of the upper limb in chronic hemiparetic stroke patients. "The WFFS measures isometric flexion/extension forces generated by the wrist, fingers, and thumb during 3-D movements of the paretic upper limb (Miller et al., 2009)." Unlike other hand exoskeletons, the WFFS is able to generalize 3-D movements of the hand in conjunction with the rest of the limb. This hand exoskeleton acts as a lightweight, portable, and rigid forearm orthosis of the ACT^{3D} robot, an arm coordination training device. This allows for measurements of wrist and finger forces during any tasks that the ACT^{3D} normally performs.

2.4.3. EVA

One research focus is geared towards assisting astronauts in extravehicular activities or EVA. The current gloves used by NASA are less flexible than desired, requiring mechanical work to displace the glove and to hold the glove in any given position. This additional required work reduces EVA productivity and fatigues astronauts' hands. Work has been done to create a motorized hand exoskeleton with the ability to perform a power hand grasp and a precision finger grasp. The design consisted of a series of drivers, mechanical stops, sensor arrays, four bar linkages, DC motors, and cable driven cam systems. Human hands are particularly complex with over 25 degrees of freedom (Shields et al., 1997). The hand exoskeleton reduced the allotted degrees of freedom significantly, creating the system's primary shortcoming: the coupling of joints in the hand exoskeleton. The researchers found that if motion for one finger was attempted, the other fingers would also be forced to move, if only a little bit. Additionally, the sensor array would sometimes pick up hand motions that were not there, causing undesired exoskeleton motion.

A robotic apparatus called Skil Mate was introduced to revitalize almost all skilled workers on production sites by introducing cooperation between humans and machines. This project was implemented in August 1998. The aim of the project was to manufacture an exoskeletal structure to be worn by astronauts for EVA. It was designed to have no intelligence or memory, but to work synchronously with skilled workers. The exoskeletal structure covers the worker's arms, hands, fingers, body and legs (Umetani et al., 1999).

2.4.4. VR/AR-Haptic

Much of the early literature for hand exoskeletons is geared towards their use as haptic feedback for virtual reality and augmented reality environments. VRLogic's CyberGrasp is a commercially available haptic interface for the hand that delivers a force feedback system to the fingers and hand. It utilizes pull cables with brakes on their distant end to restrict movement (VRLOGIC, 2014). A hand exoskeleton was developed at the Robotics Center-Ecole des Mines de Paris that is able to support bidirectional movement for two fingers. It is capable of four degrees of freedom for each finger, but can only control one at a time through the use of a pull cable (Stergiopoulos, Fuchs, & Laurgeau, 2003). Another hand exoskeleton developed for haptic feedback is the LRP Hand Master. It is capable of supporting 14 bidirectional and actuated degrees of freedom (Tzafestas, 2003).

2.5. Ankles/Feet

2.5.1. KAFO

The reason for building the Knee Ankle Foot Orthosis, or KAFO, was to extend the pneumatically powered ankle orthosis concept to the knee and test its performance on healthy walkers. The KAFO was built with a unilateral powered knee-ankle-foot-orthosis 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) (Sawicki & Ferris, 2009).

2.5.2. GAIT

GAIT is an exoskeleton conceived as a compensation and evaluation system of pathological gait for application in real conditions as a combined assistance and assessment method of the problems affecting mobility in individuals with neuromotor disorders. Interaction with the human neuromotor system to assist locomotion requires adequate design of the components, including both the biomechanical and functional aspects. Robotic exoskeletons conceived as an aid to mobility are designed to be used in numerous environments (Pons et al., 2007).

2.6. Full Body Exoskeletons

2.6.1. BLEEX

The Berkeley Lower Extremity Exoskeleton, mentioned in the Lower Body portion of this document, is just the beginning work for the University of California, Berkeley. The researchers also plan to develop an upper body exoskeleton. After they are certain that both are capable of functioning independently, they will attempt to integrate the two systems (Kazerooni, 2006).

2.6.2. Ekso

Ekso by Ekso Bionics is a primarily lower body exoskeleton for individuals with any amount of lower extremity weakness or limb pathology related to standing and/or walking. The exoskeleton uses battery powered motors to drive the legs when the exoskeleton's sensors pick up intended movement. The exoskeleton is capable of providing natural gait and assists in gait training for patients who suffer from complete paralysis and who have minimal forearm strength (Ekso Bionics, 2014). The Ekso exoskeleton is considered a Class I medical device in the United States, a Class I medical device in Australia, and a Class IIa medical device in the European Union (Ekso Bionics, 2014).

2.6.3. HULC

Lockheed Martin's Human Universal Load Carrier (HULC) is a hydraulic-powered, titanium, anthropomorphic exoskeleton designed for military use. It is capable of carrying up to 200lbs, march at 3 mph, sprint at 10 mph, can travel 20 km on level terrain at 4 km per hour, and can be set to a long-range mode for extended 72 hour missions (HULC, 2014). The HULC weighs in at 53 lbs., is powered by lithium polymer batteries, and is capable of integrating with armor, heating and cooling systems, additional sensors, and other custom attachments.

2.6.4. TALOS

The U.S. Government has officially sanctioned a full body exosuit for military use. The Tactical Assault Light Operator Suit, or TALOS, is the planned future of warfare. The US Army requested white papers from academia, industry, public labs, and any interested individuals on how to design and build TALOS. Not much has been released on this in-development suit; however, there has been speculation that TALOS will feature an already designed exoskeleton at its core (US Army to Build…, 2014). The most likely candidates at this time are Lockheed Martin's HULC and Raytheon's XOS 2.

TALOS, when fully completed, will be bulletproof, weaponized, able to monitor vitals, give its wearer superhuman strength and perception, have layers of smart materials and sensors, and use wide-area networking and on-board computers to provide more substantial situational awareness (Army, 2014). The U.S. Army Research, Development and Engineering Command, known as RDECOM will be involved in every aspect of TALOS development.

3. THE FUTURE OF EXOSKELETONS

3.1. The Benefit of Exoskeletons

3.1.1. Personal Cost

Lo and Xie (2012) stated that exoskeleton training using in rehabilitation could potentially enable self-therapy activities without involvement of a therapist, which could reduce rehabilitation cost. Exoskeleton training could be flexible, not limited to time and location, which could reduce scheduling conflicts and provide for more frequent training. The cost associated with these problems could be reduced (Lo & Xie, 2012).

3.1.2. Rehabilitation

Rehabilitation improvement relies on intensity of training and patients' motivation. Recent studies on exoskeleton for rehabilitation indicate that an exoskeleton can provide training at different levels and more frequently compared to traditional therapist training. Experimental results also indicate that exoskeleton assisted training is effective for daily living activities, which could benefit stroke patients recovering from neurological and orthopedic damages (Mihelj, Nef, & Riener, 2007). Games are integrated into some exoskeleton training activities. Training processes are designed as games in order to provide patients with an entertaining experience, which can increase their motivation to complete therapy (Housman et al., 2007; Lo & Xie, 2012).

3.1.3. Industrial Application

An exoskeleton can be used as a human assistive device in industrial environments by reducing the load on the human body, which would extend human capabilities. In virtual reality, the exoskeleton can be used as a haptic device to allow human users to interact with virtual objects by parameterizing proper force based on the virtual objects' characteristics. Additionally, exoskeletons have served as master devices for manipulating control systems (Rosen et al., 2005).

3.1.4. Military Application

To enhance a soldier's capability and reduce their workload, exoskeletons were developed to assist soldiers with increased carrying and firing ability for heavy weapons (Winder & Esposito, 2008). There is plenty of room for research in military application.

3.2. What Don't We Know About Exoskeletons?

The most critical challenge lies in the design of a controller to allow natural movement of a highly articulate prosthetic with minimal ethical and physical invasion. For the foreseeable future, the first step is to create a mapping from EMG patterns to muscle forces; this should be a primary research focus over the next three to four years. This method of control will allow individual finger movements coordinated with the hand, wrist, and elbow, unlike anything current prosthetics can accomplish. This will significantly increase the quality of life for the wearer, as well as the utility of any prosthetic. Furthermore, perceiving and exploiting the intricacies of low-level neural signals will open the door for deeper understanding of cortical control and other methods tapping into spinal or peripheral nerves, thus jumpstarting the field of neuroprosthetics (Dellon & Matsuoka, 2007).

Actuator and power supply technologies still have limitations. Current actuators are unable to provide both a high power-to-weight ratio and high bandwidth, while modern power supplies have insufficient energy density (Lo & Xie, 2012). PMA has a high power-to-weight ratio but lacks bandwidth, while motors have sufficient bandwidth but have a poor power-to-weight ratio (Lo & Xie, 2012).

Current mobile exoskeleton robots rely on a lower limb exoskeleton to carry the weight of the actuators and power supply. Although this has been shown to be a feasible approach with the recent success of the full body HAL-5 exoskeleton for assisting the elderly and physically weak, improvements on the weight and efficiency of the actuators and power supplies are needed to achieve better exoskeleton performance (Lo & Xie, 2012).

Another limitation is the singular configuration present in exoskeletons with a 3DoF shoulder complex, which occurs when two rotary joints align with each other, resulting in the loss of 1DoF. The current method used to address the problem merely shifts the configuration to an uncommon posture rather than eliminating the configuration from the upper limb workspace (Lo & Xie, 2012).

There is limited consideration of the interactions between the exoskeleton and the human user. No major study has made any attempt to assess exoskeletons specific to human labor. Beyond work related to rehabilitation exoskeleton research does not effectively consider biomechanical or degenerative aspects of exoskeleton design on the human. The mechanical HRI location and interface area for optimal load transfer and comfort have not been considered in current exoskeletons (Lo & Xie, 2012).

The attachment locations of mechanical interfaces and EMG electrodes will inevitably vary each time the exoskeleton is worn. To enable better use of exoskeletons in practice, the device needs to be able to adapt to variations without long calibration downtimes.

3.3. What Can We Do to Make Exoskeletons Better?

There are at least two areas related to the mechanical design of exoskeletons that show promise and have largely been overlooked. An improved understanding of walking and other movement may lead to more effective exoskeleton leg architectures (Dollar & Herr, 2008). Gait models based on actual machine elements that capture the major features of human locomotion may enhance the understanding of human leg morphology and control, and lead to analogous improvements in the design of efficient, low-mass exoskeletons (Dollar & Herr, 2008).

Investigation of non-anthropomorphic architectures may provide solutions to some of the problems associated with closely matching the structure of an exoskeleton to the wearer, such as the need for close alignment between joints of the wearer and the exoskeleton (Dollar & Herr, 2008). More research is required on recreational exoskeletons that augment running and/or jumping ability (Dollar & Herr, 2008).

Besides enabling technology and mechanical design, there are at least three issues related to the implementation of exoskeletons and active orthoses that needs further studying (Dollar & Herr, 2008). An exoskeleton with good mechanical strength, less weight, sufficient grip force, low power consumption, a computational capability compatible to control scheme, and high speed of operation (Singh & Chatterji, 2012) would be an ideal design.

The design of structure is one area where an imaginative design may reduce a lot of stress from weight constraint. The grip force and power consumption can be addressed by the proper choice of actuators (Singh & Chatterji, 2012). The ideal requirements include the material for the mechanical structure having mechanical strength, flexibility, and weight like bone; the controller having computational capability, speed, and adaptability like a brain; the actuator having high torque and flexibility like muscles; and the feedback elements having sensing capability like skin (Singh & Chatterji, 2012).

EMG is a relatively new technology. It has definite potential to be used as a control signal for multifunction prostheses. Correlation must be drawn between physiological factors, physical factors, and EMG signals (Singh & Chatterji, 2012). Advanced algorithms need to be developed to extract useful neural information (Sing & Chatterji, 2012). One of the innovative aspects is the combined use of electroencephalogram (EEG) and EMG to relay information for controlling the lower-limb exoskeleton (Singh & Chatterji, 2012).

3.4. What are the Issues Faced in Designing for Exoskeletons?

3.4.1. Power Supply (Power Density)

Current power supplies have insufficient energy density for truly mobile exoskeletons (Lo & Xie, 2012). Large, heavy power supplies limit portability and are one of the major factors limiting the application of exoskeletons outside of clinical therapy (Lo & Xie, 2012) and other "grounded" (mounted to a wall or stand) applications. Some researchers have proposed interim solutions such as mounting upper body exoskeletons to powered wheelchairs (Kiguchi et al., 2008), but improvements on the weight and efficiency of power supplies are still needed to achieve better exoskeleton performance (Lo & Xie, 2012).

3.4.2. Degrees of Freedom vs. Complexity of Model

"A mechanism that synthesizes a human-type motion will necessarily also be complex, particularly from the control standpoint. Therefore, researchers in this area have often tried to reduce the number of degrees of freedom to as great an extent as is practical (Shields et al., 1997)."

In designing a prototype hand exoskeleton (Shields et al., 1997), researchers reduced complexity by reducing DoF to one per finger, but discovered problems with this approach. "The human hand has over 25 degrees of freedom, many of which are coupled by the ligamentous structure and location of tendon insertions. This coupling was clearly evident during exoskeleton tests (Shields et al., 1997)," in which undesired exoskeleton motion was observed. "One obvious solution to this problem is to add more degrees of freedom to the exoskeleton. This will unfortunately also result in added complexity, weight, and bulk, not to mention a more sophisticated controller (Shields et al., 1997)."

Researchers involved with the BLEEX lower body exoskeleton took a different approach to this tradeoff. "Each BLEEX leg has 7DoF..., but actuating all of them creates unnecessarily high-power consumption and control complexity. Instead, only joints that require substantial power should be actuated… [S]ince the primary goal of a lower-extremity exoskeleton is locomotion, the joint power requirements for the BLEEX were determined by analyzing the walking cycle…. (Zoss, Kazerooni, & Chu, 2006)" Additionally, the hip and other joints were simplified such that overall the BLEEX represents a "near anthropomorphic" design (Zoss & Kazerooni, 2006).

3.4.3. Mobility/Wearability

Many existing upper body exoskeletons overcome weight or bulk issues by being mounted to a wall or stand, or to a wheelchair (Lo & Xie, 2012). This is adequate for applications where a limited and defined workspace is involved, or where a patient requires a wheelchair. While lower body and full body exoskeletons bear their own weight, there are many applications for which a wearable, "ambulatory" orthotic or assistive device is all that is needed. Improvements in mass, power density, and actuation are necessary precursors to widespread use.

3.4.4. Aesthetics (in Some Applications)

The aesthetic appeal of the exoskeleton will eventually have to be addressed, at least for some applications. For example, like many current exoskeletons, WOTAS was designed as a platform to explore a specific concept, and not as a final orthotic solution. While it successfully demonstrated the feasibility of mechanical tremor suppression, it was too bulky and heavy to be used day-to-day (Rocon et al., 2007). "The main wish expressed by the potential users was the possibility of hiding the exoskeleton under clothing (Rocon et al., 2007)."

3.4.5. Variability/Uncertainty Within the Same Person

Skin surface EMG signals are often used as a control input because they directly reflect the intentions of the user, but EMG-based control is difficult to realize due to several issues. Obtaining the same EMG signals for the same motion is difficult even with the same person. The activity of antagonist muscles affects the joint torque. Many muscles are involved in a single joint motion, and additionally, one muscle is simultaneously involved in more than one motion. The role of each muscle for a certain motion varies in accordance with joint angles, the activity level of some muscles such as bi-articular muscles are affected by the motion of other joints (Kiguchi et al., 2008), and EMG signals can vary due to muscle fatigue (Lalitharatne et al., 2013).

Additional uncertainty is related to the differences between humans and machines. "The exact locations of the human joint axes of rotation cannot be known on living subjects, due to coverage of the joints. Biological joints are not ideal "single DoF" joints, but have rather complex joint surface geometries, which cause shifting axes of rotation during motion. Additionally, fixation of a robotic device on a human limb is never rigid, such that slippage between the device and the limb will occur. This will lead to further misalignment between the mechanism and human joints (Schiele & van der Helm, 2006)," on the order of a few centimeters. Such misalignment can lead to pressure sores on the skin, long-term joint damage, joint dislocation and cartilage damage, and stumbling (Schiele & van der Helm, 2006).

3.4.6. Variability Between Persons

The activity level of each muscle and the way of using each muscle for a certain motion is different between persons (Kiguchi et al., 2008). Several solutions have been proposed to provide adaptive control between users: adjusting impedance (Kiguchi & Hayashi, 2012), myoprocessors with optimization ("gene" modelling) (Calvallaro et al., 2006), adaptive gain (Kang & Wang, 2013), and neuro fuzzy modifiers (single) (Gopura et al., 2009).

3.4.7. Safety

Safety is of paramount concern with robotic systems, especially for robots that must interact with humans. Unfortunately, "there is no industry-standard approach to designing these safety-critical robot systems. Numerous safety-critical software systems have been developed and deployed in other domains ranging from aircraft flight management systems to nuclear power plants (Roderick & Carignan, 2005)." Similar analytical methods, such as fault tree analysis, should be applied to the design of robotic exoskeletons. Some common concerns with these systems are moving the human outside of their safe position range, moving the human at an excessive velocity, and applying excessive torque to the human or allowing the human to apply excessive torque against the robot.

The system reaction to fault detection must also be carefully considered. For example, upon fault detection, the system could be commanded to either halt motion or power to the affected motors. Removing power has the undesirable effect of leaving the human to bear the weight of the device, which presents hazards of its own. This approach is only appropriate in response to more severe failures (Roderick & Carignan, 2005).

The safety requirements for mechanical design of the upper body exoskeleton include "axes deviation of wrist flexion/extension axis and wrist radial/ulnar axis" should be satisfied; "ill effect caused by the movement of the center of rotation of shoulder joint due to upper-arm motions should be canceled out"; and "mechanical singularity should not occur within the workspace of the robot (Gopura et al., 2009)."

The two main aspects that need full consideration are (Schiele, 2007) implementation of the actuation and motor control, and intrinsic mechanical and kinematic design of their structure. To ensure human safety when using an exoskeleton, a mechanical constraint combined with software limitations is the most popular method. CADEN-7 uses mechanical constraints to prevent excessive movement of body segments. CADEN-7 also uses a pulley in the design to enable slip when limitations are reached. The electrical system of CADEN-7 contains three shutoff switches to set electrical constraints. Gupta et al. also used mechanical stops and control limitations to ensure safety (Gopura et al., 2009).

4. CONCLUSION

Development of assistive exoskeletons began in the 1960s, but advances in technology have spurred a broad spectrum of research aimed at enhancing human performance and helping the physically weak. Orthotic exoskeletons are aimed at rehabilitation, posture support, and replacing lost function. Performance augmenting exoskeletons have potential use in the military, emergency services, disaster response, construction, industrial applications, and space applications, among others, and can also provide a haptic interface with virtual reality or augmented reality displays. Lower body, upper body, hand, and foot/ankle exoskeletons have developed separately due to specific challenges with each, but with a goal of full body integration, with some designs envisioned as full body exoskeletons from the start.

The key technologies of exoskeletons involve sensing the user's intent and actuating the movement of limbs based on that intent. Some of the remaining challenges include improving the energy density of exoskeleton power supplies, improving the power to weight ratio of actuation devices, avoiding singularities within the workspace, improving the mechanical human-machine interface, and dealing with variability between users and within the same user. Further improvements in computing power, reductions in overall weight, and increased understanding of human movement will enable further advances in exoskeleton design.

Additional issues faced in the design of exoskeletons are the tradeoffs between degrees of freedom and complexity, both mechanical and algorithmic, as well as mobility, aesthetics, and safety. A failure to account for the strength of the human system in the design of exoskeletons can easily result in injury. Safety is of paramount concern in systems where robots must interact with people, and analytical methods similar to those used in other safety-critical software systems should be applied to exoskeleton design.

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