State of the Art and Future Directions for Lower Limb Robotic Exoskeletons

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***Abstract*—Research on robotic exoskeletons has rapidly expanded over the previous decade. Advances in robotic hardware and energy supplies have enabled viable prototypes for human testing. This review paper describes current lower limb robotic exoskeletons, with specific regard to common trends in the field. The preponderance of published literature lacks rigorous quantitative evaluations of exoskeleton performance, making it difficult to determine the disadvantages and drawbacks of many of the devices. We analyzed common approaches in exoskeleton design and the convergence, or lack thereof, with certain technologies. We focused on actuators, sensors, energy sources, materials, and control strategies. One of the largest hurdles to be overcome in exoskeleton research is the user interface and control. More intuitive and flexible user interfaces are needed to increase the success of robotic exoskeletons. In the last section, we discuss promising future solutions to the major hurdles in exoskeleton control. A number of emerging technologies could deliver substantial advantages to existing and future exoskeleton designs. We conclude with a listing of the advantages and disadvantages of the emerging technologies and discuss possible futures for the field.**

***Index Terms*—Gait, human performance augmentation, powered orthoses, rehabilitation, wearable robotics.**

I. INTRODUCTION

THE goal of this review is to summarize the state of the art for lower limb robotic exoskeletons and discuss ways to advance the field. Summarizing the current state of the art is difficult because new devices appear in media or press releases every month. A review of devices will inevitably become dated but there is still value in assessing what research groups around the world are working on. We hope to facilitate researchers new to the field as they look for opportunities to make unique contributions in their own work.

We divide robotic exoskeletons into three broad categories based on their intended use. The first category is human performance augmentation exoskeletons for increasing strength, endurance, and other physical capabilities by able-bodied individuals. This type of exoskeleton could be used for lifting heavy objects, carrying heavy loads over large distances, or working with heavy tools. The likely settings for these devices are in warehouses, construction sites, emergency relief operations, or military bases and excursions. The second broad category encompasses assistive devices for individuals with disabilities. Stroke, spinal cord injury, muscle weakness, and other neurological or musculature disorders can lead to difficulty walking or making arm movements. Current estimates suggest that in the United States alone there are 11.7 million individuals with difficulty walking and 8.8 million individuals with difficulty lifting objects [1]. Assistive robotic exoskeletons can allow users to complete movements they could not complete on their own. For example, many of these exoskeletons are intended to allow an individual with lower limb paralysis to walk with the aid of crutches. The third broad category is therapeutic exoskeletons for rehabilitation. These devices can assist, resist, or perturb the user's movements to achieve therapeutic exercise. They can train an individual's muscles and/or nervous system to help them overcome the limitations of a disability when they are not using the exoskeleton. There are some devices that cross over between assistive exoskeletons and therapeutic exoskeletons. These bi-functional exoskeletons could eventually be helpful for therapy as well as increasing the current physical capabilities of the user when it is worn.

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II. CURRENT STATE OF THE ART

A. Limitations in Design and Performance Details

Assessing the current state of the art in robotic exoskeletons becomes very difficult for two reasons: the speed of technology development and the availability of scientific publications in the field. These issues will be addressed in the last section of the review more extensively, but they deserve mention here. As you read the following section on devices that are in development, we will try to highlight the various technologies that are being incorporated into the devices and the lack of peer-reviewed journal articles that describe or test the devices.

B. Human Performance Augmentation Metrics

There is no established gold standard for assessing robotic exoskeletons for human performance augmentation. The most common metric is measuring the metabolic cost of locomotion under walking or running conditions with and without the exoskeletons. For devices that are focused on solely assisting able bodied individuals with locomotion, metabolic cost is clearly the most accepted standard. Very few studies have shown a statistically significant decrease in metabolic cost during locomotion while using the exoskeleton. As designs, hardware, and control systems improve, the hope is that more robotic exoskeletons will actually provide an energetic benefit to the user for walking and running. It is much more difficult to evaluate robotic exoskeletons that provide assistance for lifting objects or performing work with tools. Energetics are just one aspect of the task. Fatigue, productivity, and safety are all very relevant and important factors for these exoskeletons.

Another commonly used metric for exoskeleton is the analysis of electromyography (EMG) signals. Users respond to exoskeleton assistance by modifying muscle activity patterns. Quantifying EMG data helps to understand the underlying effect of the exoskeleton on the user's biomechanics. A common goal of many exoskeletons is to reduce muscle recruitment in the lower limb during locomotion. This is often measured by surface electromyography but musculoskeletal modeling [2] and ultrasound imaging techniques [3] can be used as well.

Fig. 1. FORTIS exoskeleton (left) was designed by Lockheed Martin for industrial use. The X1 exoskeleton (middle) was developed in a joint collaboration between NASA and IHMC and may see use in the future as an exercise trainer in space to help prevent astronauts' muscles from degrading in microgravity. The Wyss Institute is developing a soft exosuit (right) under DARPA's Warrior Web program.

C. Human Performance Augmentation Devices

In 2000, the Defense Advanced Research Projects Agency (DARPA) started a large funding initiative on robotic exoskeletons that helped propel the field forward in a large leap. This program, Exoskeletons for Human Performance Augmentation (EHPA), was focused on augmenting the capabilities of unmounted soldiers [4]–[6]. While a number of different research groups and technologies were initially funded, two exoskeleton prototypes were the most visible. The Berkeley Lower Extremity Exoskeleton's (BLEEX) goal was to develop a portable robotic exoskeleton that allowed soldiers to carry heavy loads over long distances [7]–[10]. A key feature in the design was that the weight of the device and backpack load went to the ground through the exoskeleton frame rather than onto the user. The BLEEX had actuated joints at the hip, knee, and ankle for both lower limbs. The major limitations of the BLEEX device were in its large mass, limited joint range of motion, and control. Although the exoskeleton weight and backpack load was transmitted to the ground through the frame, there was still considerable mass to the device, affecting the inertia of the user's movements. The controller used kinematic and kinetic sensors to essentially get out of way of the user's limbs during movement. Thus, there was always a noticeable lag between the time the user initiated a movement and the exoskeleton's actuators reacted. The second exoskeleton prototype that was developed with major DARPA EHPA funding was created by Sarcos, a robotics company founded by Stephen Jacobsen. The Sarcos exoskeleton [6], [11] evolved into XOS after Sarcos was acquired by Raytheon. The Sarcos exoskeleton was a full body suit that supported both the arms and legs with the intent of amplifying the user's strength. The exoskeleton powered its joints by rotary hydraulic actuators connected to a tethered power source. Due to the high electrical energy demands of the prototype, it was not made fully portable. It was controlled with force sensors that were instrumented on both the user and the exoskeleton in an attempt to minimize the amount of contact force between the user and the exoskeleton [11]. As is common with most robotic exoskeleton development projects, the Sarcos team did not publicly provide details of their design or its performance. Very few quantitative results are available to assess the success of the device. Now under continued development at Raytheon, a new version has emerged that is purported to be much more energy efficient than the original design [12]. Extensive reviews of the DARPA exoskeletons and others developed during that time frame are available by Herr [13], [14].

Lockheed Martin is one of the most prominent developers of exoskeletons to augment human performance. They acquired the Human Universal Load Carrier (HULC) exoskeleton technology from Berkeley Bionics (now called Ekso Bionics). The HULC is based on the BLEEX design and is meant to allow soldiers to carry heavy loads over long distances. A test on an early prototype performed by the U.S. army showed that the exoskeleton changed gait characteristics and led to an increase in metabolic energy expenditure [15] and also a decrease in functional range of mobility [16]. Advancements in the HULC design have been advertised, but like many exoskeletons in development, there is a lack of quantitative assessments of the device available to other researchers. A closely related exoskeleton called FORTIS was recently announced in a press release by Lockheed (Fig. 1). It is intended specifically for industrial use in shipyards [17]. The FORTIS device allows the user to more easily handle and manipulate heavy tools using Equipois' ZeroG arm. Unlike HULC, FORTIS is unpowered but its ability to transfer load to the ground may reduce fatigue and improve safety.

There are a number of other companies around the world developing similar human performance augmentation robotic exoskeletons. No published scientific documentation exists on most of these devices but some information can be gleaned from press releases and web sites. A South Korean company called Daewoo Shipbuilding and Marine Engineering has also developed a robotic exoskeleton for helping shipbuilders carry heavy loads [18]. A French engineering company called RB3D has been developing a robotic exoskeleton called Hercule for the French army with a similar design goal as Lockheed's HULC (i.e., offloading weight through the exoskeleton) [19]. An upper limb component allows users to carry 20 kg in each arm. The Hercule claims to be able to operate nearly silently and allow users to walk 20 km on one charge. The Body Extender exoskeleton similarly has upper and lower limb capabilities with 22 actuated degrees of freedom and the capability of handling loads up to 50 kg in one hand [20].

Fig. 2. Ankle–foot exoskeleton (left) from Hugh Herr's lab at MIT actuated the ankle joint and demonstrated a reduction in metabolic cost compared to walking without the device. Another ankle exoskeleton (middle) developed by Greg Sawicki and colleagues also showed a metabolic cost reduction during walking but without actuation. Only a very few exoskeletons have been designed for human running to date. The Michigan running exoskeleton (right) had a parallel spring component to the leg and functioned primarily passively.

The B-Temia/Revision Prowler exoskeleton is intended for military personnel in combat. Little substantive information or publications exist on the performance of any of these devices.

The X1 exoskeleton (Fig. 1) was built as a joint effort between NASA and the Institute of Human and Machine Cognition in Pensacola, FL, USA. It was intended as a potential means for training astronauts in space to prevent muscle fatigue and bone thinning [21], [22]. The device can be configured in a force-control mode allowing both eccentric and concentric exercises.

One of the most recent innovative designs comes from Conor Walsh and his research team at the Wyss Institute. They have developed several soft wearable devices that can provide powered assistance to human movement [23], [24]. The suits (Fig. 1) are different than typical rigid exoskeletons with heavy metal frames and motors. The project is funded by the DARPA Warrior Web program and is moving the field in a novel direction. However, they have not yet been able to show substantive reductions in energetic cost using the device.

There have been a large number of prototype robotic ankle exoskeletons developed [25]–[34], sometimes referred to as powered ankle–foot orthoses. Results from these robotic ankle exoskeletons have been encouraging but not overwhelming. For example, we have shown reductions in EMG activity and metabolic cost during walking by able-bodied individuals with nonportable robotic ankle exoskeletons [35]–[37]. One of the few studies to date to show a reduction in metabolic cost using a portable exoskeleton (Fig. 2) came from Mooney and colleagues at Massachusetts Institute of Technology (MIT), Cambridge, MA, USA [38]. The authors developed a lightweight powered ankle–foot orthosis that delivered plantar flexion assistance at push-off of late stance. The device led to an 8% average reduction in metabolic cost for users with the exoskeleton compared to without the exoskeleton. Another recent ankle exoskeleton device has achieved a reduction in metabolic energy consumption for walking without any powered assistance at all [39]. A passive ankle exoskeleton using clutches and springs was able to lower metabolic cost by 7.2% compared to walking without the device (Fig. 2). There are no robotic ankle devices that have been commercialized at present.

Some exoskeletons have been designed for augmenting running for able-bodied subjects and have relied on passive elastic mechanisms. The MIT design included an exoskeleton knee that attached to the thigh and shank [40]. A clutch was used to lock the knee at peak knee extension to provide resistance during stance, but unlocked during swing for free movement. The authors found a 25% metabolic increase when using the device even though the parallel spring provided around 18% of the sum biological and exoskeleton stiffness. Similar results were seen for the Michigan running exoskeleton [41]. The Michigan design (Fig. 2) was different in that it had multiple elastic elements at the knee and ankle, but it also provided compliance in parallel to the biological lower limb. The Michigan exoskeleton was also connected all the way down to the shoe, transmitting external spring load to the ground [42]. Some of the difficulties with running exoskeletons include the faster limb movements during running compared to walking and the need to have low resistance during the swing phase. This means that running exoskeletons need to be incredibly lightweight to give support during stance that is not negated by the extra work required to support the exoskeleton in swing.

D. *Assistive Technology Devices for Impaired Populations*

Many research laboratories and companies are primarily working on robotic exoskeletons with the intent to assist individuals with disabilities. We distinguish between exoskeletons primarily intended for assistance to perform tasks and those that are primarily designed for therapeutic purposes. This section focuses on the array of different exoskeleton devices that have been designed to assist impaired populations with additional locomotion function. While reducing overall metabolic cost is still a dominant goal for this group of exoskeletons, it may not be the most important one. For patients who are typically wheelchair bound, the primary goal is simply to give them enough safety, support and balance to walk. An often used clinical measure in these populations is a determination of preferred walking speed, usually with the 6-minute walking test. A higher preferred walking speed indicates a better clinical outcome as walking speed is well associated with social mobility.

One of the oldest and most well-established exoskeleton technologies for disabled assistance is the ReWalk [43]. This exoskeleton was recently FDA approved for use with spinal cord injury patients. The ReWalk bilaterally actuates the knee and hip joints to enable walking, standing, and sit-to-stand maneuvers for patients with SCI [44]. Patients control the high level function of the device with a remote control and carry the batteries and controller in a backpack. A few notable clinical studies have been performed with the ReWalk [43], [45], [46]. Some of the limitations of the device include its bulk, wrist controls, and complexity of learning how to control it.

Cyberdyne is a Japanese company that has helped to develop and market the Hybrid Assistive Limb (HAL) exoskeleton technology (Fig. 3). The technology is for use by patients with incomplete spinal cord injuries, stroke and other deficits that impair walking functions [47]–[51]. HAL has both unilateral and bilateral versions that actuate the knee and hip joints. It is the only lower limb exoskeleton on the market today that utilizes the

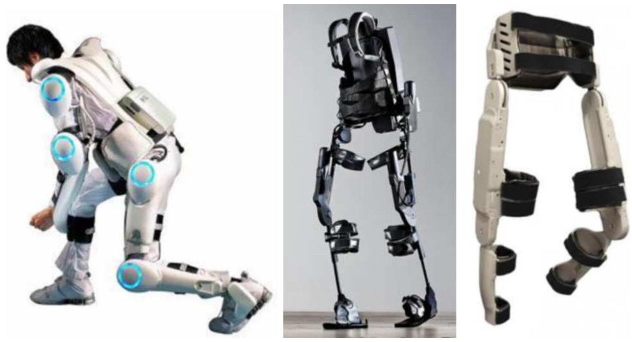

Fig. 3. A number of exoskeletons have been developed for assistive purposes for impaired populations. Cyberdyne (left) developed the Hybrid Assistive Limb (HAL) exoskeleton to aid individuals with disabilities. This includes both arm and leg assistance that can be used separately or in tandem. HAL is one of the few commercial devices controlled by neural signals from the muscles (EMG). The HAL system has seen extensive use in Asia and Europe in clinics. The Ekso exoskeleton (middle) is used primarily for rehabilitation purposes by clinics around the world. The Ekso helps provide gait training for patients recovering from a lower limb disability such as spinal cord injury. The Indego exoskeleton (right) from Parker Hannafin is intended as an assistive technology exoskeleton to aid persons with spinal cord injury.

remaining surface electromyography (EMG) signal information from its users. The EMG signal is nonlinearly related to joint torque and it can provide a greater level of patient interaction with the device compared to kinematic and kinetic sensors alone [52]. In earlier studies, researchers demonstrated the feasibly of using surface EMG control for HAL [53] and even showed a reduction in muscle use for one subject when the system provided active assistance for a variety of tasks [54]. HAL has been an innovative leader in exoskeleton technology for over a decade and is especially unique in that it has included neural signals in the control loop from the beginning of its development. The limitations are hard to assess given the lack of performance data in the literature and the lack of widespread use outside Japan.

Ekso Bionics has developed the Ekso exoskeleton (Fig. 3) device to assist disabled individuals with walking and lower limb movement. Similar to the HAL and ReWalk exoskeletons, the Ekso bilaterally actuates the knee and hip joints. It is currently primarily used under the guidance of a physical therapist for gait training and can provide the therapist with manual controls for the device. The feasibility for using it has been demonstrated for spinal cord injury [55] and larger scale clinical trials are in progress around the world. The main drawbacks with the device at this point appear to be the limitations in gait speed and flexibility to adapt to changes in the gait environment or task.

Honda has developed two walking assistive devices: one called the stride management system and one called the bodyweight support system. The stride management system from Honda is quite different from others in that it only actuates at the hip joint [56]. Honda recently announced a collaboration with the Rehabilitation Institute of Chicago to perform a clinical trial on the walking assist device focused on stroke patients [57]. Few details are available on the engineering of the devices.

The Indego exoskeleton (Fig. 3) is being marketed by Parker-Hannifin for people with spinal cord injuries. The Indego bilaterally actuates both the knee and hip joints and attaches around the waist which stores a battery pack. Because the Indego exoskeleton originated from a university research laboratory, more information is available about the design than with exoskeletons designed in an industry environment. The Indego uses a joint-level controller that functions in either a PD mode, which sets high gains to try to enforce a prespecified joint angle trajectory [58], or impedance mode in which the controller virtually emulates a spring-damper system [59]. The higher level control consists of a finite state machine that governs each individual controller. The state machine is responsible for allowing the user to change between modes such as sitting, standing and walking [59]. An interesting advantage to the Indego system is that it is modular, allowing it to be broken down into smaller pieces for transportation when not in use. There is not enough performance data available yet to assess its major limitations.

Rex Bionics has developed the REX Personal that is able to walk and navigate slopes and stairs. REX is significantly different than other exoskeleton designs in a number of ways. The technology completely encompasses both legs and the user stands on foot platforms while the machine physically walks for the user with minimal user interaction necessary. Researchers at various institutions have used REX in experiments to integrate brain control using EEG into the device [60], [61]. The biggest limitations of the device at this point are its extremely slow gait speed and very large bulk.

The MINDWALKER exoskeleton was developed to assist spinal cord injury patients with noninvasive brain control [62] and is solely a research device at present. The exoskeleton bilaterally actuates the knee and hip (both flexion/extension and ab/adduction) and uses a state machine to switch between actuation modes while walking [63]. One study analyzed EMG activity in healthy and SCI subjects and found changes in patterns for both upper and lower limb, but it was not helpful for reducing overall muscle recruitment [64].

E. Exoskeletons Designed to Provide Therapeutic Benefit

As exoskeletons have been increasingly developed for clinical populations, many of the devices might also provide therapeutic benefits to the disabled users who wear the devices. Wheelchair bound individuals often experience secondary complications from disuse such as lower limb muscle and bone loss [65]. Providing individuals that are normally wheelchair bound with additional opportunities to become weight bearing and physically active is a fundamentally sound strategy for improving their physiological health [66]. Using robotic devices for therapeutic gait training is not new either. Stationary treadmill-based robots such as the Lokomat, LOPES and ALEX devices have been employed by rehabilitation laboratories and hospitals around the world [67]. Given the potential for long-term benefits, some research teams are designing mobile exoskeleton devices specifically for therapeutic benefits in recovering patients.

An exoskeleton device with considerable clinical experience is AlterG's Bionic Leg. Intended exclusively as a therapeutic device, it is commercially available and primarily targets stroke patients. As a unilateral device, it is worn on the knee of the affected lower limb. It augments knee strength with a powered joint directly in line with the knee's center of rotation [68]. A number of small scale clinical tests [69]–[73] have demonstrated an increase in basic walking and balance scores using a variety of clinical tests. The devices main limitations are its large bulk, weight, and limitation to unilateral therapy.

III. Engineering Design Aspects

Many core aspects of exoskeletons have converged on common solutions, even though design goals of the exoskeletons can be quite different. Common solutions in exoskeleton design choices have occurred for actuators, sensors, energy supplies, control strategies, and materials.

A. Actuators

On board actuation has been a fundamental issue throughout exoskeleton development. Size, weight and power efficiency of motors have historically limited robotic exoskeletons. Vukobratovic's foundational research went through multiple actuation models and demonstrated some of the initial difficulties with pneumatic and electric actuation [74], [75]. To provide the physiological torques required, a significant amount of weight, inertia and size needs to be introduced to the exoskeleton to house the actuators, batteries, and controllers. However, technology has improved significantly since exoskeletons began to be developed and clever new designs have taken advantage of these advances to produce portable and highly functional devices. Of the state-of-the-art exoskeletons considered in this review where design information is available, 72% of them have used electric motors (supplementary online appendix, Table I). Hydraulic and pneumatic are less common. The convergence to electric motors is likely for multiple reasons. Servo motors are capable of very advanced position-based control that is much more difficult to achieve with pneumatic or hydraulic systems. Almost all the exoskeletons that work with spinal cord injury and other disabled individuals use electrical motors to allow for some form of position control and to coordinate many degrees of freedom as most designs have at least 1 degree of freedom per joint and even up to 22 degrees of freedom with the Body Extender. Brushless dc motors are popular in exoskeletons due to their high torque to weight ratio, reduced noise, and reliability. They have been used in many devices such as the Indego, the Honda Walking Assist, and the ankle exoskeleton by Mooney and colleagues. Series elastic actuators are another popular design choice in exoskeletons such as the X1 and MINDWALKER. This is due to advantages including low output impedance, high back-drivability, high fidelity force control and capability of energy storage in the spring element to reduce overall power requirements [76]. Batteries used to power electric actuators have become more feasible with lithium ion technology by reducing size and weight and increasing power density. Due to the relatively fast movements of the legs during locomotion, gear ratios cannot be made too large, which limits the torque assistance of electric actuators. In the applications that involve military use or heavy lifting for industrial applications, the hydraulic actuators are more likely to allow for a larger amount of assistance. Hydraulics have the highest power to mass ratio, 300–600 W/kg, compared to electric motors or pneumatics which often have power to mass ratios between 100–200 W/kg [77]. However, unlike electric motors and pneumatics, hydraulic actuators power to mass ratio increases with increasing weight—which means that they are more suitable for large, bulky exoskeletons that require high torques and less so for smaller designs. While soft pneumatic actuators have advantages in weight and compliance, the compressed air generator needed to use them limits their potential use in portable systems. Electric actuators are likely going to continue to play the largest roll for exoskeletons as their size, weight, and output torque are sufficient for most applications.

B. Sensors

Sensors of some form are necessary for controlling robotic exoskeletons. Every exoskeleton in this review has at least some form of mechanical sensor to help regulate position, force, or torque (supplementary online appendix, Table II). Most exoskeletons encode joint position which helps to regulate safety and provides a phase variable to modulate torque output. Additionally, many lower limb exoskeletons use a position controller and try to specify a precise joint angle trajectory that the exoskeleton cycles through each stride. Many, but not all, exoskeletons also use force sensors. Most commonly, these involve a foot sensor that measures ground contact force and may even be a simple on/off switch to detect heel contact and toe off. This helps by providing different control states for stance and swing phase and can sometimes be used for more sophisticated measures and control such as calculating center of pressure. Hall effect sensors have also been used to ensure proper motor torque output in some exoskeletons. Accelerometers and gyroscopes are occasionally included but have not been well documented as being critical or as improving control schemes. While on board mechanical sensors are nearly ubiquitous in exoskeleton designs, additional types of sensors are not as common. It is unclear currently whether additional sensors are needed for robotic exoskeletons, or at least worthwhile for improving exoskeleton control. Mechanical sensors to monitor other parts of the body are rare, with the exception of a switch to specify control states (such as initiating standing). Neural and/or muscular sensing have been proposed in many research papers and may have significant potential if current obstacles can be overcome. The only commercial lower limb system to use EMG as a controller input is HAL, but there are several research prototypes that have used EMG sensors. Brain and neural signals have yet to be used in any commercial application, but researchers in multiple groups have proposed using EEG sensors for high level spinal cord patients [61], [62]. Invasive muscular, neural or brain recordings have not yet been used for commercial exoskeleton controllers to date. Rigorous studies comparing sources of information for exoskeleton control are rare if nonexistent. Many types of mechanical and neural signals have been used for higher level intent recognition to various degrees of success and are summarized well in a recent review by Tucker *et al.* [78].

C. Energy

Power supply has traditionally been stated as one (if not the largest) issue in the development of portable exoskeletons. More energy requires more weight which tends to decrease the overall functionality of a given exoskeleton. Almost all exoskeletons use batteries to generate the necessary energy for a powered system (supplementary online appendix, Table

III). Thus, the success of robotic exoskeleton technology is substantially tied to changes in battery technology. The expanded availability of lithium ion batteries has allowed many exoskeleton designs to function during continual movements for 1–5 hours. Many clever designs have incorporated passive mechanical elements such as springs and clutches to store and release energy similar to biological tendons. The XPED2 exoskeleton was designed to store energy in springs with a system of cables and pulleys to transfer energy between the exoskeleton joints [79]. It failed to reduce metabolic cost as predicted by previous modeling [80], but a simpler passive exoskeleton that augmented only the ankle joint reduced metabolic cost [39]. Additionally, regenerative braking [81] can be included to make use of the eccentric portions of the gait cycle and recover a portion of the energy. These designs along with improved batteries can enable portable exoskeletons to function over a significant period of time, to the extent that these exoskeletons could be practical in everyday situations.

D. Control

Unlike actuation, sensing, and energy supplies, control strategies for exoskeletons tend to vary widely from one design to the next (supplementary online appendix, Table IV). The two most common forms of control are direct force (or torque)-based control and kinematic, or position-based, control. For force-based control, two different strategies are commonly applied. One is to perform an open-loop form of control such that a prespecified force or torque value is applied based on the assumed portion of the gait cycle. This strategy may incorporate other variables such as walking speed or step length to the formula but is difficult to optimize across multiple conditions such as jogging, slopes, and stairs. A more responsive controller is a proportionally applied force/torque based on a specific sensor such as an EMG measurement from a relevant muscle or force sensor between the user and the exoskeleton. These are adaptable to different situations but difficult to implement in real-world devices. While it varies, a direct force strategy tends to be the preferred approach for human performance augmentation. Position-based control is more likely to be used to assist human locomotion to apply a set of predefined joint angle trajectories. This control strategy is especially useful when the user has little ability to interact with or control the exoskeleton. However, it tends to give the user the least amount of control and interaction with the device which limits its overall applicability. State machines can help address this problem and are employed in some of the designs to incorporate a combination position and force control. Due to the transitional nature of the gait cycle (particularly swing and stance phase), it is often useful to break up the controller into multiple different control states depending on phase of the gait cycle. State machines can also be further extended to allow for different states for alternate terrain such as stairs or transfers between standing and sitting among other activities. A more detailed breakdown of different controllers for many exoskeleton devices in the literature is provided in [82].

The exact control algorithms of many of the exoskeleton devices are not well documented, especially for commercial systems. Performance comparisons between controllers are rare in the literature, and typically a single control strategy is developed for each individual design. Unlike with other technologies, there is not a general convergence of solutions for exoskeleton control as a very wide variety of controls are used and their specific effects are not documented. Studies reporting outcome measures are really a function of both the exoskeleton hardware and the controller. The independent effects of the two are not well separated. This makes it very difficult to evaluate or compare the effectiveness from one proposed controller to another.

E. Materials

Another important property of exoskeletons is the frame design. The frame design may actually have a vastly underrated effect on the overall performance outcome of a robotic exoskeleton. Most exoskeletons have metal frames (supplementary online appendix, Table V). Indeed, often the concept of an exoskeleton for human use is inherently associated with a rigid metal frame as a necessity. Most exoskeleton designs employ some type of aluminum alloy to create the links between the joints of an exoskeleton. The typical goal is to keep the design as lightweight as possible, but allow for physiological forces to be conveyed between struts. Titanium is likely more ideal in terms of strength and weight for metal frames, but also substantially more expensive. Titanium alloys have a specific strength (a measure of the ratio of a material's yield strength to density) of 44-278 $\mathrm{N^*m/kg}$ which is 67% higher than aluminum alloys which have 9-166 $\mathrm{N^*m/kg}$ [83]. An alternative material that is sometimes used is fiber-reinforced plastic such as carbon fiber. These are used more often in designs that only actuate a single degree of freedom. Carbon fiber is lighter weight than aluminum and might be a promising design choice. Soft exoskeletons are also an interesting concept to help reduce weight, such as that demonstrated by the Wyss Institute exosuit. Overall, rigid metal frames of aluminum, titanium and/or steel are the common design material for any exoskeleton that actuates multiple degrees of freedom.

IV. Future Solutions to Improve Exoskeleton Control

A. Control is a Weakness in Many Designs

Technological improvements have enabled exoskeleton technology to be viable on the market. Major gains in electronics, actuators, batteries, and sensors have propelled the use and acceptance of exoskeletons further. One issue with exoskeletons has been a considerable calibration and setup time required to don the devices. However, many device makers now report donning times of only a few minutes with their modern products. Comfort and the interface to the user are still issues but are improving as exoskeletons are tested more on their user base. A significant issue that still remains is how to effectively control the exoskeletons to maximize the benefits of these robotic devices. Controllers vary widely from one exoskeleton to another, and few studies test different controllers directly on the same hardware. Additionally, most exoskeletons only employ mechanical sensors embedded in the device. While these are useful, additional information about the state of the user may prove very valuable for strengthening the control options that a user has over the device. In this section, we explore some of the promising ideas in research laboratories today that may be very useful when applied to exoskeleton technology.

B. Feedforward Neural Commands

One of the most direct ways to incorporate user input and feedback is through a neural (or muscular) link. The only exoskeletons on the market today to incorporate this type of technology are HAL and Myomo [84] which both use surface EMG electrodes. The muscular activity gives a representation of what the user is attempting to do and can be used to proportionally determine the torque generated by actuators in the device. Surface EMG, such as that used by HAL, Myomo, and other exoskeletons used in research, is useful but has a number of drawbacks such as a lack of stability overtime. Surface EMG signals change due to a variety of factors such as placement, fatigue, and sweat. This limits the practicality of surface EMG as frequent recalibrations might be necessary to benefit from the EMG. An alternative solution that holds promise for EMG-based technology is to use intramuscular EMG electrodes that may have more stable properties over time. While muscle fatigue might still change signal properties over time, other problems such as placement, sweat and electrode shift during movement will be removed. One example of this technology is the implantable myoelectric sensor (IMES) which can be powered remotely and wirelessly and sends out the myoelectric signal to a controller [85]. These sensors can be inserted with a needle and permanently reside within the muscle belly. Other groups are also working on intramuscular EMG technology [86]. This technology could be highly beneficial for the subset of exoskeleton users who have both remaining EMG activity and permanent access to an exoskeleton device.

Another technology that could be used to establish a neural link that has been researched heavily over the last decade are brain machine interfaces. A huge array of research groups have been working on these for a wide variety of purposes and can interface at the single neuron level using penetrating electrodes. Some of the most popular options available are the Utah array and Michigan electrodes. Less invasive options that still require surgery under the skull for placement (e.g., electrocorticography) are also possible. These options may provide valuable information to establish a neural link, but they come at the high cost of a brain surgery. This limits users to those with a relatively high commitment level such as spinal cord injury patients. Descending nerves at the spinal cord or periphery are another possibility to tap into neural activity for control, and potentially combine with stimulation for biological feedback. A peripheral nerve interface has been implanted in humans and successfully demonstrated [87] with an amputee patient.

All of these technologies have the potential to provide a feedforward neural command that could be highly beneficial for exoskeleton control. Muscle and nerve signals are produced prior to force generation, a concept known as electromechanical delay. This small delay period could enable a device to react to a given neural command and generate appropriate torques to be in line with the user's intentions. This could greatly improve control options for exoskeletons, but all of the invasive technologies such as intramuscular EMG, nerve recordings and brain recordings have a significant drawback in that an electrode or electrodes must be placed in the body for the long term. This may be acceptable for a user who relies on an exoskeleton every day such as an individual with spinal cord injury. However, many of the potential users of exoskeleton technology may only use it for short periods of time and an invasive device would not be practical or warranted. This includes able-bodied subjects who use exoskeletons for military or industrial purposes as well as disabled individuals who use exoskeletons for a limited time for health and therapeutic benefits (i.e., physical therapy). In fact, most exoskeletons in use today are for these purposes, and very few are "take-home" devices that are used by the same person every day.

A promising solution that may provide neural information for the nonpermanent users are epidermal electronics. These small electronic devices attach to the skin similarly to a temporary tattoo and have the capability of measuring EMG and EEG [88]. The EMG recordings from these may not be as stable of a measurement as intramuscular EMG but instabilities due to placement and movement should be reduced. Sweat and fatigue may still provide some changes to the EMG signal over time, but this may be an acceptable tradeoff for users who do not want permanent implants. For users with complete SCI that cannot contract appropriate muscles, the epidermal electrodes can be used in lieu of a full EEG cap and may be a practical method for providing direct neural control. Hair can be regrown through the mesh of the epidermal electrodes to potentially provide a very valuable neural signal on the scalp without the need of invasive solutions. While these still require the commitment level of a temporary tattoo, this may be a very viable tradeoff to gain neural control information for an exoskeleton device.

C. Machine Vision

Machine vision technology has been in use and improving in many different fields [89] but is a relatively unexplored technology for exoskeleton control. Sensors that analyze the visual space in front of the user such as cameras or infrared sensors have many applications for improving control. They may be able to estimate the ground slope and change control parameters appropriately to best augment the user. Additionally, sensors may detect whether the user is indoors or outdoors and change controls to deal with uneven or rough terrain. For example, on rough terrain, the exoskeleton controller might choose to walk slower but with a more stable gait pattern than it would over flat, even terrain in a building. Sensors may detect an upcoming curb or stairs to change control states for the user. Sensors may even be able to identify objects that might cause a trip or fall and provide appropriate control to help prevent falls. Information fusion approaches will be necessary to help incorporate information gathered across domains such as mechanical sensors on the exoskeleton, sensors for machine vision and possibly sensors conveying neural or myoelectric information.

D. Better State Machines

For lower limb exoskeletons, state machines are often employed to specify different states of the controller such as between stance and swing phase. Further break-downs of the gait cycle are sometimes used such as to specify a late-stance phase for powered plantar flexion or to break up swing into multiple distinct states for swing flexion (early) or swing extension (mid/late). Not all controller designs incorporate a state machine, but many have. It is a powerful tool to implement different controllers such as an impedance-based controller in stance and a kinematic controller for swing. For most commercially marketed exoskeletons, state machine specifics are not reported in detail including the entrance/exit criteria and the specific control law that defines a state. It would be valuable to report quantitative metrics that evaluate state machine parameters to help guide the evolution of controllers for exoskeletons. Many studies simply use time within stance or swing phase to determine when to apply torque and normalize to subject specific step timing. Time specific parameters should be largely eliminated from state machines and replaced with phase variables such as joint angles/velocities, limb segment movements, or ground reaction forces to allow for greater robustness over a variety of conditions such as changes to step length and walking speed. Neural information can be incorporated into the state machine architecture to provide better timing and proportionality of torque applied to movements such as ankle plantar flexion during late stance or hip flexion at toe off. Hybrid controllers can be developed to take advantage of useful neural information and resort to more basic mechanical sensor information when the neural information is not available, useful, or clean. Machine vision may help to enable more robust transitions between control states or provide information for a controller that incorporates ground slope into the torque formula. Also of use would be to determine the optimal way to enable robust transitions between states within a state machine such as standing to walking, transitioning between sitting and standing, and transition to take a step up/down a stair or curb. Overall, our recommendation is to have state machine logic presented and evaluated using quantitative metrics such as metabolics, kinematic, kinetics, EMG as well as the effects on walking speed, gait symmetry, step length, balance, and other biomechanics of gait parameters. This will help determine best practices for state machines that may enable exoskeleton designs to become more capable and viable in the future.

E. Artificial Neural Oscillators

An interesting controls approach that has been proposed for legged robotics is to use artificial neural oscillators. These are based on the idea of a central pattern generator, and have been proposed to provide a robust and adaptive framework for controlling multi-DOF systems in varying environmental paradigms [90], [91]. These are potentially promising for cyclical tasks such as locomotion and have promising simulation results. These systems can help to exploit the natural resonance within a mechanical system such as an exoskeleton to help reduce energy cost [92]. Such a system has been applied to an upper limb exoskeleton [93] but could also be an interesting approach for lower limb to help reduce energetic cost [94] and improve robustness. They have been successfully implemented in powered hip exoskeletons to help relate hip joint angle to joint torque [94], [95] and predict gait cadence [96]. Their key advantages include the ability to adapt to different walking cadences, implementation using a range of different sensors, and lack of user dependent calibration.

V. Future Projections Regarding Hardware

Outside of the controllers, there is still considerable room for improvement for much of the exoskeleton hardware. The components that need the most work relate to the frame (comfort and energy transmission) and the actuators.

Another frequent comment by users of robotic exoskeletons is that the soft tissue interface between the device and the user's body is not particularly comfortable. Human skeletons are routinely powered by muscles that attach directly into bones. This is an ideal situation for transmitting torques and energy to the skeletal system, both for efficiency and for remaining pain-free. When humans don most robotic exoskeletons, they have skin, fat, and muscle in between the exoskeleton and their own skeletal system. Compressed soft tissues can become painful when using powered exoskeleton. The pain of robotic exoskeleton use becomes worse when the exoskeleton does not contain enough degrees of freedom for fluid motion. Compressed soft tissues also becomes a huge energy sink, decreasing the transmission efficiency of mechanical energy. In some cases, as much as 50% of the mechanical energy of the robotic exoskeleton is lost as work to compress soft tissues. New designs of exoskeleton frames that incorporate a combination of materials (such as carbon fiber and synthetic textiles) along with more traditional metals may have more success in transmitting energy from the actuators to the user's body. The DARPA Warrior Web program has recognized this limitation in past rigid, metal robotic exoskeleton frames and has actively pushed researchers into the direction of softer, more form-fitting devices. Incorporation of 3-D printers that can use multiple types of materials to create subject-specific frames may also hold potential for minimizing both pain and energy loss during use. Including greater degrees of freedom into the exoskeleton frame would allow the device to better match the motion patterns and complexity of the human body. In past devices such as BLEEX, the movement pattern during walking was considerably modified by the device, making locomotion seem unnatural and forced (not to mention metabolically costly). Starting with a complex enough model to capture the anthropometry of the human body could facilitate the creation of a frame that does not hinder the movement patterns of the user.

The presence—or absence—of additional passive degrees of freedom within an exoskeleton has been largely unaddressed in the literature, but is critical to the success of a device. When walking in whole body exoskeletons, passive degrees of freedom (or the lack of them) drastically affect how encumbered the user is when attempting to maneuver and turn. Past biomechanics studies have found that limiting the range of movement and/or the degrees of freedom increases metabolic cost and decreases gait performance [97]–[100]. Additional basic science research that expands beyond level walking on a treadmill is needed to explore the importance of different passive degrees of freedom, especially at the hip and pelvis [101].

Although the majority of robotic exoskeletons have relied on electrical motors in the past, the size and weight of current actuator designs can be limiting. An alternative approach would be an investment in truly novel actuator designs that do not resemble current standards for autonomous robots. Going back to how human muscles are configured, actuators that only pull and are very lightweight can present some distinct advantages to traditional electric motors. This aspect is recognized by the ongoing research sponsored by the DARPA Warrior Web program. Improved actuator designs could have a large effect on the viability of robotic exoskeletons for human performance augmentation.

One approach to advancing the field would be to focus on smaller, single joint robotic exoskeletons rather than continued pursuit of large, whole body robotic exoskeletons. Past studies have shown that human exoskeleton users can more readily adapt to a single joint exoskeleton than a multiple joint robotic exoskeleton. This may be due to the difficulty in adjusting the internal model of movement dynamics on the fly if the changes made are more extensive. Improving the performance of single joint exoskeletons through better controllers and actuators would then presumably lead to further development with whole limb exoskeletons.

In the near future, the commercial success of robotic lower limb exoskeletons is most likely to occur in smaller niche markets. Much of the military focus at present is for all-purpose robotic exoskeletons that can function in the combat zone. This requires a much greater mechanical performance level and a very flexible controller. Alternatively, when exoskeleton users are in constrained settings (e.g., warehouse, construction plant) and perform a limited number of constrained tasks (e.g., moving boxes, ship construction), the robotic exoskeleton assistance can rely on simpler devices and controllers. It seems reasonable to expect that these simpler devices for a limited range of tasks (like the FORTIS) will be able to show commercial viability before the all-purpose battlefield devices. In addition, getting the smaller and simpler devices to market would likely help jump start the field as a whole. Once there is more widespread commercial acceptance of some robotic exoskeletons, secondary technology suppliers are likely to develop and add to the number of workers and companies in the industry. Honda has been working towards this idea with their hip assist exoskeleton [102] and Lockheed Martin has shifted to focusing on FORTIS with a similar intent.

VI. Future Projections

It is a great time to be in the field of robotic exoskeletons. Technological advancements in the hardware are making new designs and prototypes feasible that were not realistic ten years ago. There is continued interest in funding exoskeleton research. The National Robotic Initiative has pooled together resources from the National Institutes of Health (NIH), National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), Department of Defense (DoD), and U. S. Department of Agriculture (USDA) to provide continued stimulus on robotics research. Within the NRI robotic exoskeletons have had a predominant role. TALOS is another effort to accelerate the development of robotic exoskeletons that may lead to fast gains in commercial technology [103]. The TALOS program seeks to make a tactical exoskeleton suit that incorporates body armor, power, soldier monitoring, and weaponry.

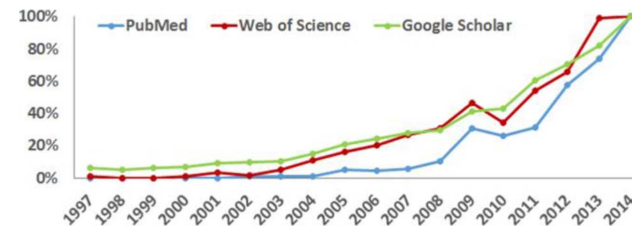

Fig. 4. Number of publications on robotic exoskeletons over the last 18 years as a percentage of the 2014 level. The number is expressed as a percentage of the 2014 year level for the three different data base sources. For the year 2014, PubMed Central had 137 publications in its database, Web of Science had 120 publications, and Google Scholar had 2710 publications, all using the keywords "robotic exoskeleton". The number of publications across all three doubled from 2004 to 2009 and doubled again between 2009 and 2013.

The program has brought together industry and academic experts to assess technical limitations and determine paths forward to develop a military-ready suit. The project is funding a number of different groups to advance specific technologies, but only a few have been officially announced, such as Revision's Prowler exoskeleton technology which includes lower limb enhancements and armor plates [104]. The TALOS technological developments are likely to help further push along the development of exoskeletons for augmenting human movement and capability. However, there is the concern that by aiming only for the all-purpose superhuman robotic exoskeleton for combat zones, they will miss the opportunity to develop near term commercial successes in smaller niche markets.

Although many companies discourage scientific publications on their devices, there is a promising trend for the field. A search of various scientific databases reveals exponential increases in the number of peer-reviewed publications on robotic exoskeletons for assisting human movement (Fig. 4.). Advances in other technologies are also going to accelerate success of robotic exoskeletons. Wearable sensors will provide new information on human intent and motor status. Big data algorithms will need to be incorporated to mine the vast amount of physiological signals that will be available in the near future [105]. Machine learning techniques that take advantage of apprenticeship training enable a dizzying array of tricks in model helicopters [106] and may bring new control approaches to robotic exoskeletons. The 3-D printing of materials [107] will allow for customization and cost-effective approaches to exoskeleton frames and hardware in a way we have not seen previously.

As the field moves forward, it is likely that there will be more disappointments before there are big successes. An interesting perspective on emerging technologies is given by the Gartner Hype cycle [108]. The Gartner Hype cycle is a visualization of how advanced a given technology is in everyday life. Robotic exoskeletons fall under the category of Human Augmentation in Gartner's annual analysis. Robotic exoskeletons are still on the curve of inflated expectations, with at least 10 years until reaching a steady level of productive use in the real world. In a perspective paper from 2009 [109] one of us predicted that by 2024, it would be common to see people walking down the street and in the community while wearing robotic exoskeletons. That prediction is still possible, but there are concrete obstacles that must be overcome to reach it. This review paper has laid out some of the major challenges standing in the way.

From a big picture perspective, there are clear objectives that can facilitate successful robotic exoskeletons in the near future. We need engineers to work with kinesiologists [110]. Kinesiologists know how the human body works in a way similar to how engineers know how machines work. When a human wears a robotic exoskeleton for movement assistance, the movement pattern quality is wholly dependent on the interactions between human and machine. An understanding of neural control, energetics, and musculoskeletal biomechanics is crucial to getting a successful exoskeleton. We need industry to work with academia. Rapid prototyping capabilities and knowledge of product design in industry can greatly aid academic researchers in trying outside of the box approaches to robotic exoskeletons. It will also lead to more quantitative documentation about device performance in the archival database through journal publications so that scientists/engineers can learn from each other's mistakes. We need funding agencies to value basic science projects on robotic exoskeletons. Too many times the review of grant proposals prioritizes just building new devices. Understanding how humans interact and adapt to robotic assistance is critical to creating better designs in the future for devices. We need better theoretical frameworks of energetic cost, neural adaptation, and biomechanical function to feed into the designers. Scientists and engineers need to work together to pursue these objectives if the field is to accelerate towards commercially successful devices.

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