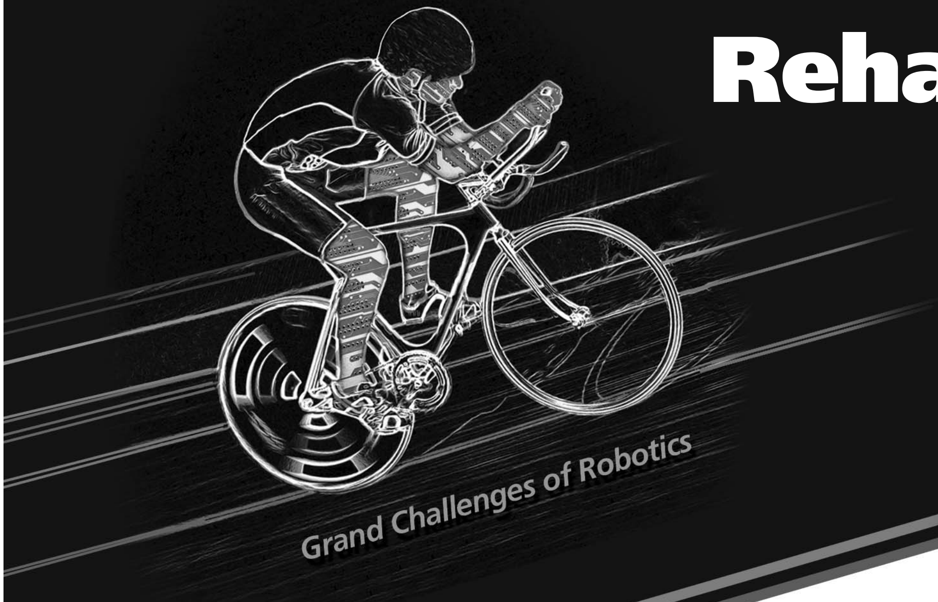
Prosthetics, Exoskeletons, and Rehabilitation

Now and for the Future



BY BRIAN DELLON AND YOKY MATSUOKA

In the near future, the need for assistive robotic devices will increase. During the 1950s, only 4.9% of the world's population was over the age of 65. Today, almost 20% is over 65 and this figure is predicted to exceed 35% by 2050. This demographic shift in world population will impose a large burden of care to treat the health risks associated with aging. Robotic solutions will help tackle these issues and enable the elderly to regain their independence and maintain an enriching, fulfilling lifestyle.

The benefits of robotic systems are not limited to healthcare. Applying these technologies to military applications allows soldiers to carry more and walk further. However, the style of recent wars creates additional needs for robotic assistance: while the death toll has been dramatically reduced (10% of injured died in Iraq compared to 30% in World War II), 6% of injury survivors required amputation (compared to 3% in previous wars) and 20% of injury survivors will need permanent assistance for the rest of their lives.

Robotic systems for assistance and rehabilitation focus on providing missing movements and sensing, providing safer environments, and providing environments that make regaining movement-related function easier and faster. Robotic prosthetics and exoskeletons will provide dexterity, natural mobility, and sense of touch to missing or paralyzed limbs. Individuals suffering from hip or knee conditions can use a robotically intelligent walker or wheelchair to help prevent common accidents like slipping. Finally, robotic rehabilitation not only provides consistent and efficient therapy without tiring, it also has the potential to enhance the therapy beyond the abilities of the practitioner.

When this field reaches its zenith, the benefits to society will be enormous. We will be able to replace entire limbs with prosthetics that can replicate one's own biological functions precisely, casting a natural outward appearance and requiring minimal upkeep. With a safe and intelligent robotic rehabilitation unit, patients can recover faster and more naturally without feeling resistance to repetitive exercise or the need to be in a hospital. These are neither dreams nor hubris, but goals to strive towards.

However, these goals cannot be achieved without tackling some technical challenges that lie ahead. As a robotic community, many of the challenges in the field of prosthetics are common

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to other physical human-robot interaction (PHRI) fields: power, size, weight, and safety. When users are disabled or elderly, these challenges must be met even more rigorously. Furthermore, perhaps our biggest and most unique challenge ahead is to grow closer to the fields of neuroscience and movement science, and to the clinicians in these fields, so that more natural controls may be realized, all towards the goal of robotic solutions actually being employed in medical practice.

History and Present

Brief History of Artificial Limbs

The evidence of prosthetic usage dates back as early as the ancient Egyptians. In one case, it was found that a mummy's big toe had been amputated during its life and supplanted with a carefully crafted wooden toe, which attached by a series of wooden plates and leather strings. The oldest known leg prosthesis from 300 BCE was discovered in Capua, Italy, and was made out of copper and wood. In the 16th century, prostheses were created from iron for soldiers by the same blacksmiths who crafted their suits of arms. An iron arm had the ability to flex a fully digital hand. By the 19th century, James Potts created a leg with artificial tendons to lift the toe when bending the knee.

Interest in artificial limbs increased during the American Civil War, due to the large number of amputations that occurred during this time. The advances in technology that occurred were primarily due to the discovery of anesthetics. Anesthetics enabled longer surgeries so the doctor could better shape the stump, providing a better fit for the prosthetics.

Present Prosthetics

Given how long ago these solutions were available, the current solutions for limb prosthetics may not appear vastly different. However, newer materials and electronics have made prostheses more functional since they are lighter, more compliant, and more adaptable to specific stump shape or personal style. The state-of-the-art C-Leg (www.ottobockus.com) (Figure 1) has a carbon fiber frame, a built-in computer to analyze data from multiple sensors, and a hydraulic cylinder that actuates the knee and matches the user's gait on various terrain. These devices have reached such a high performance level that users are able to participate in athletic events.

Unlike lower-limb prosthetics, upper-limb prosthetics are not yet dexterous enough to provide function comparable to healthy limbs. Commonly used upper-limb prosthetics (Figure 2) range from a hook to a single-degree-of-freedom (opening and closing) mechanism using myoelectric control. Upper-limb prosthetics with multiple degrees of freedom typically use sequential control methods, with locking mechanisms or switches used to separately activate each joint. There is a lot of room left to improve these unnatural control mechanisms.

For the last decade, the research focus in upper-limb prosthetics has been in the anthropomorphic arm and hands capable of neural interface. The Cyberhand (www.cyberhand.org),

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with a single degree of freedom per finger, aims to interface with both afferent and efferent pathways, providing true feedback for the user. The ACT hand [1] is designed around the central tenant that an anatomically correct hand can be operated by the same neural signals used to operate the muscles in the original hand (Figure 3).

Present Exoskeletons

Exoskeletons have been used in a variety of movies in the last century, but the technology has only recently enabled the

Figure 1. *C-Leg. Copyright Ottobock Healthcare.*

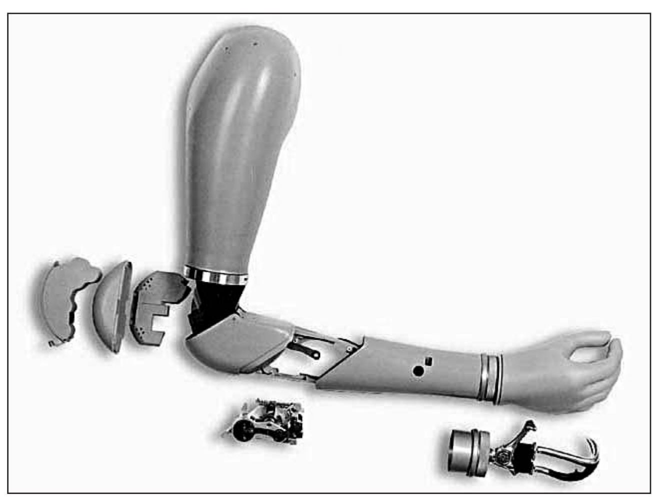

Figure 2. *Utah Arm. Copyright Motion Control.*

development of a light, compact system for real use. The Berkeley lower extremity exoskeleton (BLEEX) (Figure 4) is capable of carrying more than 75 lbs at 3 mi/h, yet it weighs only 30 lbs and incorporates a regenerative power system. These systems are getting closer to providing realistic power augmentation for soldiers, firefighters, emergency personnel, and industrial workers to use for carrying heavy loads and extending their physical abilities [3]. The Hybrid Assistive Limb (HAL) is an exoskeleton designed to assist the elderly and disabled individuals by using the user's myoelectric signals to control the exoskeleton movement. However, it is also strong enough to augment the user's power by 40 kg. While these lower exoskeletons have recently made a giant leap, hand exoskeletons are still too bulky and difficult to fit to hands of different shapes and sizes.

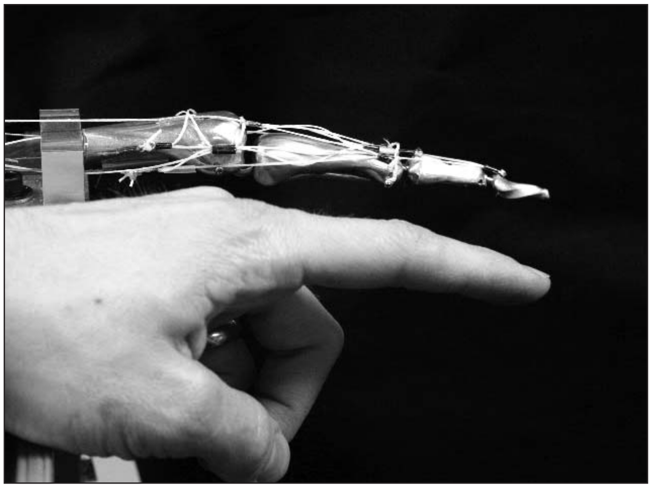

***Figure 3**. Anatomically Correct Testbed (ACT) index finger. Copyright Neurobotics Laboratory*

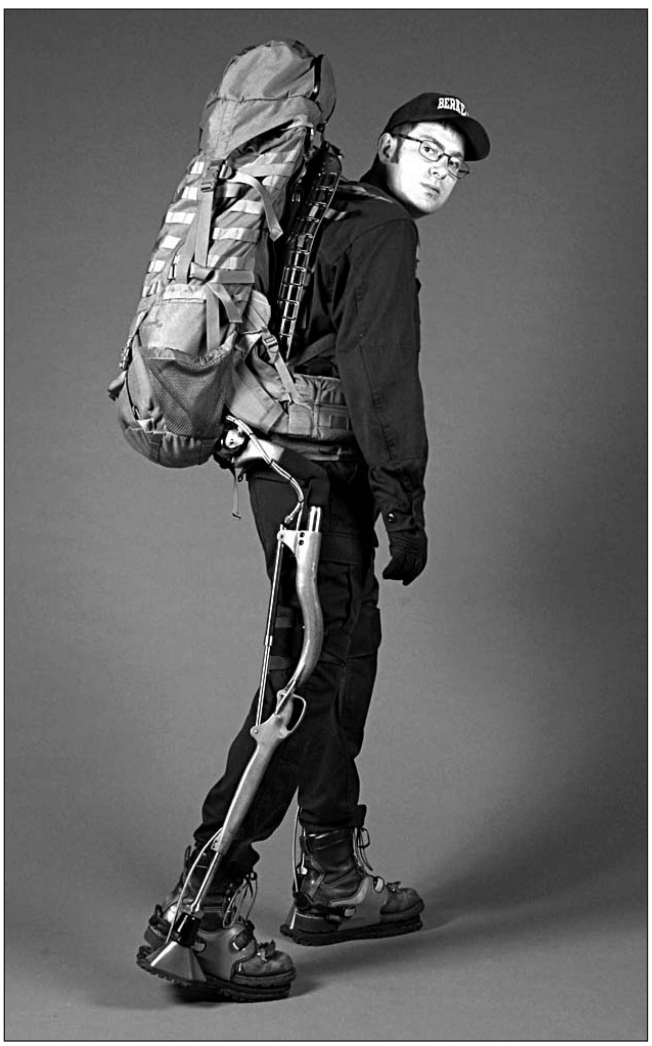

***Figure 4.** BLEEX exoskeleton. Copyright Berkeley Robotics and Human Engineering Laboratory*

Present Robotic Rehabilitation

The field of robotic rehabilitation is a couple of steps ahead of prosthetics and exoskeletons, mainly because the robotic devices do not have to be worn by the user. This means that the robotic devices do not have the same power or size constraints. A variety of haptic devices for upper limbs [MIT-MANUS, PUMA (MIME), PHANTOM, WAM] and lower limbs (i.e., Lokomat) are used in research to show the clinical efficacy in physical therapy for stroke and other neurological disorders with movement disability (Figure 5). The main challenge of this field lies in showing the efficacy of these regimes. While it is acceptable to show an equal amount of improvement compared to human therapists if the robots are used as a tool to increase the volume/frequency of patients treated, we also would like to see that taking advantage of the robotic precision in sensing and actuation results in faster and more complete recovery than traditional therapy. Because robotic rehabilitation challenges are not as critically in the robotic science path, the rest of this article focuses more on prosthetics and exoskeletons.

Challenges

The challenges in prosthetics and exoskeletons are in three areas: electromechanical implementation, the use of neural control signals and extraction of intent, and the interface between the robotic and clinical communities.

***Figure 5.** MIT MANUS. Copyright Curt Campbell, VA Palo Alto Health Care System*

Electromechanical Implementation

Designing a fully functional bio-mechatronic analog of the human arm and hand is an extremely difficult proposition. Replicating the complexity of the entire range of limb movements is hard enough provided infinite weight and size, but it needs to be accomplished within a slender morphology, replicating the look and weight of a human limb. It is also critical that it withstands the rigors of daily life.

These requirements are only met with the development and integration of durable, light, and flexible materials, small and powerful (yet low cogging) actuators, high spatial and temporal resolution tactile sensors that conform like human skin, small connectors and wires, small controllers with amplifiers, and a light and long-lasting power supply. Each of these components requires scientific breakthroughs. As a roboticist, the challenge is to push the envelope of the integrated electromechanical systems with the existing components. One good example was displayed by the BLEEX exoskeleton, which uses one-way power limiting. This method of control enhances safety and allows for regenerative energy cycling.

One of the biggest challenges for robotic systems that interface with humans intimately is to assure the safety of the user. While everyone recognizes the importance of this, there is no standard available that is appropriate for the current human-robot interaction. In ANSI/RIA R15.06 guidelines, the only guideline available for PHRI, effective segregation of humans and robots is outlined. It is important to establish a safety guideline appropriate for elderly and disabled human users and to develop and integrate both mechanical and electrical safety systems in exoskeletons, prosthetics, and assistive rehabilitative devices.

To meet stringent standards, redundant safety mechanisms must be in place. Other factors such as limiting power output, limiting velocities in Cartesian space, and using a backdrivable system to reduce reflected motor inertia should be considered. One critical consideration is the placement of sensors. Having a single force sensor on the end of a manipulator is not enough to provide forceful interaction of the complimentary portion of the device with the environment. Sensing and reacting to all forces and torques, on all powered surfaces and under all conditions (including power failure), dramatically increases safety.

Neural Control Signals and Extraction of Intent

Assuming the electromechanical challenges are met, we are left with the challenge of designing a controller based on physiological signals as its input. The human arm has seven degrees of freedom, and the hand has more than 20. These degrees of freedom must be controlled in a meaningful, natural, and perhaps optimal way; thus the key to this dilemma is developing a better intelligence to drive the device [2].

Control Signals

While joysticks and voice commands are used for some of the commercially available systems, the trend is to use the neural signals to attain the user's "intent," which naturally exists when he or she executes a task. There are a variety of ways to tap into the neural information, ranging in hierarchical location (cortex, spinal cord, peripheral nerves, and nerve ending at muscles) and invasiveness [direct electrodes (needles/cuffs in tissue)] of surface electrodes [electromyography (EMG) or electroencephalography (EEG)]. While direct electrodes provide more localized signals (single neuron, single motor unit, etc.), surface electrodes are less invasive and provide diffused but more global signals. With the current level of understanding in neuroscience, it is easier to understand the "intent" of the signals recorded from muscles (the neural signals arriving at muscles must be used to contract muscle fibers) than to decode the "intent" of individual neurons in the cortex. For these reasons, surface muscle electrodes have been one of the most popular techniques used thus far as the control signals for exoskeletons and prosthetics. Muscle signals from weakened muscles or from the stump are ideally gathered and amplified for control. However, due to the limited signals available from local muscles near the point of injury or paralysis, other unrelated muscle signals are used (for example, using the shoulder muscles to control hand grasp).

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Extraction of Intent

Unfortunately, getting the user's intent is not simple even for muscle-level neural signals; the relationship between the neural signal arriving at the muscle (called muscle activation) and the muscle force or position is not known. One of the common approaches is to simply set a linear (or other simple) mapping between the muscle activation and the force of the robotic joints and have the user learn this mapping. This is a reasonable task for healthy subjects to complete for a small number of degrees of freedom. However, it is difficult to learn this unnatural mapping and to control any more than one or two degrees of freedom. Thus, the biggest challenge lies in achieving the control of high degrees of freedom (such as in the human hand) in an easily learnable format. This is one of the main reasons for investigating cortical or higher neural signals that may contain synergistic or behavioral "package" information. Population of neuronal coding has been linked to the limb's end-point movement direction, speed, and force. This coding structure in the cortex is used to drive a robotic arm in three dimensions [5]. In the most recent approach taken by Northwestern University, peripheral nerves are surgically rewired to pectoral muscles and the amplified muscle activation signals are used to control a prosthetic arm and hand [6]. While this configuration still does not provide any more than one degree of freedom for the hand, the patient has shown a remarkable ability to learn to control several degrees of freedom, resembling natural arm coordination. A variety of these approaches should be pursued further to enable natural coordination of multiple joints and limbs.

Clinical Interface

The final, and perhaps the most important, challenge in the area of robotic systems for rehabilitation, exoskeleton, and prosthetics is the usability of the system. These systems must be driven by what the users will use, even if it is a 30-year plan. This means that the device must present intuitive control mechanics, be easy to don or doff, and be comfortable, silent, and aesthetically acceptable. The aesthetic needs are often neglected even though this is one of the most important features users desire as a way to conform to the societal norm. Furthermore, the clinicians who prescribe these devices must be in agreement with the approach. Nobody wants to build a device that will simply be placed on a shelf in a physician's office to collect dust. To assure that these challenges are met, there must be a novel way to allow greater communication between clinicians, users, and engineers.

Grand Challenge

There are many significant roadblocks standing in the way of future prosthetics. 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 determine a mapping from EMG patterns to muscle forces; this should be a primary research focus over the next few 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 drastically increase the quality of life for the wearer and 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.

Conclusions

While the funding atmosphere is generally poor at the National Institutes of Health and the National Science Foundation, big challenges in this field must be overcome to keep up with the rapid growth in the elderly population. The Defense Advances Research Projects Agency (DARPA)'s "Revolutionizing Prosthetics" project kicked off recently with the aim of producing–within this decade–a fully functional (motor and sensory) upper limb prosthetic that responds to direct neural control. The culmination of these efforts promises to result in a lightweight, high-degree-of-freedom prosthetic arm and hand. Prosthetics has been one of the poorly funded areas, and hopefully this effort will also generate future possibilities for funding.

Acknowledgments

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Keywords

Prosthetics, exoskeletons, rehabilitation, neural control.

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