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Lower Limb Orthotics Society

The Evolution of Powered Orthotic Technology

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Introduction and History

Physical therapists at rehabilitation centers have had access to assistive robotic systems like Hocoma's Lokomat® since 2001. These tethered (i.e., plug-in electric appliances) systems have now transitioned into untethered (battery-powered), user-controlled devices. These devices are not new to the world of orthotics. The first exoskeleton was patented in the United States in 1941: A spring-based hip-knee- ankle-foot orthosis (HKAFO) that stabilized and assisted the wearer to ambulate short distances became the reciprocating gait orthoses (RGO) that we know today.[1,2] As powered lower-extremity orthotics (pLEOs), referred to as exoskeletons in popular and research literature, are slowly incorporated into O&P clinical practice, they have attracted increasing attention from the media.

A quick PubMed search for the terms "powered orthoses" or "exoskeleton" will show the accelerated interest in pLEOs over the last decade. The earliest article on powered orthoses was published in 1989; exoskeleton followed closely in 1991. Several review articles dig for historical perspective on high-level ambulatory orthoses/exoskeletons. Research into modern pLEOs can be traced back to the 1970s, in what was then Yugoslavia, by Vukobratovic et al.[3] Advancements in motors, electronics, and batteries have led to most of the breakthroughs in pLEOs. Most importantly, Arazpour et al. show in a study of five spinal cord injury (SCI) patients, the average energy cost of walking with a powered orthosis is less than that of walking in an RGO, and also less than with an HKAFO.[4] The decrease in energy cost is associated with increased walking distance for the powered orthosis over the RGO and HKAFO.

Research teams are developing power-generating (i.e., assistive) and energy-storing (i.e., harvesting) systems. On the assistive track, the scope of research has expanded beyond offering SCI survivors independent ambulatory status to assisting other clinical populations to attain more efficient gait mechanics. Several of the commercially available designs are modular in nature and can be set up as single-limb or even single-joint devices. The benefits of symmetrical gait are becoming better understood as a result. Most designs still incorporate the foot—either inside or outside the shoe—in order to transfer the weight of the device directly to the floor, instead of hanging the added weight on the wearer. A footplate also allows for weight-shift under the foot to act as a control input, adding another factor to the control program that already measures joint angles, accelerations, and segment (e.g., shank or thigh) inclination. Some of the designs incorporate electromyogram (EMG) control as a means of single-joint response to the wearer. Others integrate functional electrical stimulation (FES) for assistance from the wearer's weak or paralyzed muscles in order to decrease the electrical demand of the motors.

Developing joint power has been managed through linear actuators, rotary motors, and pneumatic muscles. Linear actuators are fairly common in the automotive industry for opening tailgates, power-sliding side doors, and power seats. They are typically driven by screw gears and have different ranges of movement, power, and speeds, and they must cross the joint to be moved. A linear actuator can push and pull. Rotatory motors are the basic electric motor design. These are often placed at or near the joint to be moved and geared for movement range or power. These can flex and extend a joint by running in either direction. Finally, pneumatic muscles are mechanical copies of a skeletal muscle—elastic cylinders surrounded by a loose, braided material, typically carbon fiber. When the elastic cylinder is filled with air, it expands circumferentially into the braided material. As the braided material and elastic cylinder expand circumferentially, they shorten linearly, which moves the joint. These artificial muscles can only pull. This means that one provides flexion and a separate pneumatic muscle must provide the extension power for any given joint. The lightweight (aside from the air source) and unidirectional nature of these muscles has allowed for their proliferation in many projects across multiple research groups. *(Author's note: View YouTube videos of pneumatic muscles by searching for "McKibben muscle.")*

Power-Harvesting Designs

Power-harvesting research has developed prototype devices, but they have not become commercially available. The research has focused primarily on two designs. The first is a self-contained device that stores the energy it produces for a short time. The stored energy is then used to generate power or to control other functions of the device in another part of the gait cycle. The second group of designs is pure energy-harvesting devices, typically used for healthy individuals, to capture power that could be used by another device.

In pursuit of these designs, groups have examined the spikes in plantarflexion and attempted to capture the "extra" motion of the knee during loading response or terminal stance into mid-swing. A team at the University of Illinois at Urbana- Champaign (UIUC) captured the first and third ankle rockers to allow for a smooth second rocker and lock the ankle for swing-phase toe clearance. Its design is purely mechanical.[5] Researchers at Simon Frasier University, Burnaby, British Columbia, Canada, used a slip clutch on their knee-motion capture system to generate electricity. This allowed their design to spin in one direction, eliminating the need to invert the electricity generated when spinning in the opposite direction (i.e., extension instead of flexion). They determined that the knee flexion of loading response and terminal stance needed to be uninhibited; they were able to capture the final degrees of flexion in early swing and all of the extension from the remainder of swing phase.[6,7] These simple, functional designs may lead to integrated systems that provide some of the energy needed for the computational controls of more complex powered orthotic designs.

Power-Generating Designs

The AFO, the smallest device and crossing a nearly hinge-like joint, is one of the more researched powered orthotic devices. Limitations on the weight of the complete system, the amount of force that must be absorbed and subsequently generated at high rates of power, and overall cosmesis appear to limit powered AFO designs significantly. A few groups have worked in this design space, but nothing has been commercially launched to orthotists.

Hugh Herr, PhD, an associate professor of media arts and sciences and head of the Biomechatronics Group at the Massachusetts Institute of Technology (MIT) Media Lab, Cambridge, has experimented with a linear actuator-driven design.[8] His custom electromechanical setup measured ankle angle and plantar foot pressures to provide controlled plantarflexion and dorsiflexion power with a single, posteriorly placed actuator (Figure 1). The MIT AFO was further developed into a tethered device, the InMotion Anklebot, for use in rehabilitation research. The ankle joint technology with builtin instrumentation was likely transferred to some of MIT's prosthetic design work.

Figure 1: MIT's AFO.

University of Michigan (UMich), Ann Arbor, research teams (under Cain, Kao, and Ferris) have published a series of articles on control methods and design testing.[9-15] This group almost exclusively uses pneumatic muscles. They experimented with myoelectric control versus a foot switch for control of the AFO's plantarflexion and dorsiflexion actuation. They found the foot switch "learned" the step timing in about one minute, compared to 30 minutes for the myoelectric input.[16] This validates the use of a foot switch in the exoskeleton arena. This group found that healthy individuals will reduce their muscle activation to return to their familiar gait mechanics when using a powered AFO that is myoelectrically controlled.[11,17,18] This research group has also investigated other aspects of pLEOs that are beyond the scope of this article.

Building on the work of UMich, a team including researchers from the University of Minnesota, Minneapolis; the Georgia Institute of Technology, Atlanta; and the University of Virginia, Charlottesville, and led by researchers from UIUC, devised an untethered, pneumatically powered AFO.[19] Their design placed a small, compressed liquid CO_2 cylinder on a belt around the subject's waist to supply a rotary pneumatic actuator at the ankle. Their rotary actuator created eccentric deceleration at initial contact and modest assistive torque at terminal stance phase.[19] The design incorporated a shoe sole with embedded pressure sensors as the control mechanism, and an angle sensor on the actuator measured movement.

Researchers at the University of Alabama, Tuscaloosa, independently produced a very similar design using pneumatic muscles the same year.[20]

The research group at Arizona State University, Phoenix, bridged the generating/harvesting gap by using regenerative braking at the ankle to provide power to the AFO's on-board computer, which controlled the pneumatic muscle timing and power for plantarflexion through terminal stance and dorsiflexion for swing and initial contact.[21]

Research into powered KAFOs has focused on powering the knee for stair and incline ascent. By providing the knee with enough power to lift a body, it can also control descent. Controlled flexion of the knee also has been investigated to improve foot clearance in swing phase. Of particular note in this category is the work of the UMich team (Figure 2). They added to their work on the powered AFO by adding two "quadriceps" and two "hamstring" pneumatic muscles to outriggers on the thigh section.[22] This allowed them to investigate the gait effects of hamstring control via myoelectric input and inhibition through the circuitry. They found that actively inhibiting contraction of the hamstring pneumatic muscles when the quadriceps fired improved gait kinematics and energy use in healthy subjects compared to direct active control of the muscle groups through EMG. The only commercially available KAFO system is the Ottobock C-Brace®. Though the C-Brace knee unit adds the stability and control of a C-Leg to the orthotic arena, it does not actively assist in knee extension.

Figure 2: UMich's pneumatically muscled KAFO.

Several research groups looked to the hip for stability and power generation. Since one of the leading causes of falls in the elderly is hip instability, these devices may be some of the first covered by insurers. The UMich team tacked their pneumatic muscles to an off-the-shelf hip abduction orthosis. A foot switch provided the control mechanism but required three days to synchronize the timing of the flexion assistance.[23] A similar design was developed in Brazil to assist individuals without the ability to generate EMG signals.[24] Honda has commercialized an electric hip assistance device, the Stride Management Assist system, for use by able-bodied individuals as well as individuals weakened by disease and age.

Building the complexity of the device, researchers at Case Western Reserve University, Cleveland, added linear actuators to the knee joints of a mechanical RGO. The actuators were sufficient to lock the knee joints. Their particular setup was an update of one first reported on in 1989: An RGO with integrated FES. The same user was studied for both articles, written 24 years apart.[25,26]

Research into the designs that most professionals would actually describe as exoskeletons has resulted in about a dozen commercially available devices for use in heavy industries and in patient care. Devices span from restoring function to patients with injuries to improving soldiers' endurance in the field. Military funding has emphasized the improvement of fighter efficiency and the rehabilitation of injured soldiers. Commercially developed designs like Raytheon's XOS exoskeleton and Honda's Hybrid Assistive Limb (HAL) grab headlines around the globe. The science they are built upon is partially described previously. More comes from the many universities conducting research in this area, including

Tel Aviv University, Israel, which produced the ReWalk and its predecessors, and the University of California, Berkeley Robotics & Human Engineering Lab, which produced the Berkeley Lower Extremity Exoskeleton (BLEEX) system. Other full exoskeleton systems have been developed around the world with as much variation as their points of origin.

Figure 3: BLEEX, circa 2004.
Photograph courtesy of Esko Bionics.

The BLEEX system (Figure 3), for example, diverged into two

Figure 4: A soldier running while wearing the HULC exoskeleton.
Photograph courtesy of Lockheed Martin.

exoskeletons[27]: In 2008, the Human Universal Load Carrier (HULC™) was unveiled for the U.S. military (Figure 4,); and in 2010 the Ekso (then known as eLEGS) system was released to rehabilitation centers. While the Ekso (Figure 5) is a toned-down version of the HULC, which reduces lower-limb loading to increase endurance even at a running pace, it still provides four hours of walking time at functional gait speeds to users with paraplegia. The Ekso is capable of assisting the user in the sit-to-stand transition once the user transfers from his or her wheelchair into the device. The ReWalk provides capabilities similar to the Ekso for people with paraplegia.

REX Bionics' REX from New Zealand is billed as a hands-free walking exoskeleton. Released in 2010, the REX presents more like a walking robot: An assistant can walk next to the unit and control it with the input joystick on the left armrest without a user in the device. No volitional control of the lower limbs is required on the part of the user. This design forces the user to weight-shift to single-limb support while it advances the contralateral limb. At 84 pounds, it adds significant mass to move up or down a flight of stairs.

One of the most unique designs comes from Vanderbilt University, Nashville, Tennessee: An exoskeleton that crosses the hips and knees, leaving the feet and ankles free.[28] This design incorporates FES to augment the motor's power. This exoskeleton also separates into three pieces for ease of donning while the user is seated in a wheelchair. The Vanderbilt design was commercialized as the Parker Hannifin Indego exoskeleton.

HAL can be used as a single-joint device or a full exoskeleton. The lower- and upper-limb sections can be used independently or together. The lower-limb section can assist the user in squatting up to 1,760 pounds, and the upper-limb section can assist in lifting up to 154 pounds per arm. It has a sister mobility product for industrial laborers to reduce strain on the knees and hips in repetitive squatting or lifting of heavy objects. The HAL single-limb setup is now used in Japanese stroke rehabilitation centers. The knee and hip units have been used as wearable continuous passive motion (CPM) machines following surgery. Currently, HAL does require EMG input to actuate assistance.

**Figure 5: The Ekso rehabilita-
tion exoskeleton, circa 2012.** ***Photograph courtesy of Esko Bionics.***

The Future

There is still room for growth in exoskeleton design. Wearable upper-limb exoskeletons have recently come to the market (Myomo's MyoPro in 2013), while assistive robotics have been used for shoulder and elbow care for about a decade. The HAL exoskeleton is currently the most versatile exoskeleton, but it cannot achieve a running pace. Further advancements that make materials lighter and stronger, power sources smaller and more powerful (e.g., batteries and actuators), and control methods may yet yield an Iron Man-like exoskeleton for soldiers and wearable rehabilitative devices for individuals afflicted with a variety of diseases.

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