Abstract

As biomechatronic technology has matured over the past fifty years, exoskeletons have emerged as leading tools for augmenting able-bodied performance, assisting human mobility, and restoring lost limb function. These systems are anthropomorphic, structural devices that work in conjunction with the body's natural architecture to aid limb mobility. Exploiting biomimetic design, the device may be worn in close proximity to the body, and transmits torques via powered revolute joints and structural limbs. Controllable, wireless exoskeletons offer significant potential in restoring lost limb function, and enhancing mobility and strength of the user.

To date, a powered upper body exoskeleton has not been developed for the general population. Previous exoskeleton development has largely been part of major research endeavors and has yielded solutions exhibiting high inertia limbs which are burdensome to the wearer. In order to make this sophisticated technology accessible to a large population of users, our team has designed and created a proof-of-concept upper body exoskeleton for applications in physical therapy and mobility assistance.

Robust mechanical design, novel actuation methods, and embedded systems were integrated to create the Titan Arm. Our solution employs a series of controllable limbs including a powered elbow joint coupled with three unpowered rotational joints at the shoulder. As a proof-of-concept exoskeletal system, our device has met numerous performance metrics including a low inertia arm, actuation non-local to the joint, wireless power and operation, backdriveability, and low-cost development. Titan Arm offers a solution that may be extended to accessible exoskeletal systems for use in assisting human mobility and regaining limb function, allowing disabled populations such as the elderly regain independence and mobility.

Clinical Need

Physical therapy has become a standard when recovering from debilitating injuries and is crucial to the proper muscle recovery and growth. Today, there are a large number of patients receiving physical therapy, including older persons recovering from broken bones or stokes. By 2050, the number of senior citizens in the United States is estimated to double from 40 to 80 million. In addition, over 700,000 Americans suffer from strokes each year, with over half surviving, though in many cases with limited mobility. [1] The increase in aging population is present in Japan as well, with the 65+ population to increase to 30% by 2025 and 36% by 2050. [2] Besides the aging population, a large amount of injuries occur on the sports fields, requiring physical therapy to ensure a successful recovery. [3]

In order to treat an increasing number of patients, the physical therapy system must be reimagined. There is a need to reduce the load of the physical therapist and medical staff, allowing treatment for an increased number of patients. In addition, there is a need for more precise exercise instruction, so that physical therapy patients may continue therapy outside of the hospital under their own volition. Studies have shown that at-home therapy can help the elderly avoid accidents within their homes, as the increased strength decreases the chance of falls. [4]

Patients are also in need of an at-home solution for physical therapy. In an already injured state, mobility is limited and travelling to the hospital can seem almost a herculean effort. There is also the possibility of injury within transit, issues which could be mitigated by the development of a mobile physical therapy device, namely an exoskeleton. The suit must also be low in cost so as to be affordable to the hospital or personal user.

Another need within the realm of physical therapy is that of user tracking. Physical therapy can be a long and painful process, with small indications of improvement early on. The morale of the patient can be affected negatively, leading to attrition in the continuity of therapy. With a way to track development over time, the attrition rates could be decreased and morale increased for users.

Current methods available include the Ekso Bionics lower body exoskeleton. This suit allows those with limited lower body strength to walk again, reviving the ability to look their loved ones in the eyes. This suit is targeted at lower body rehabilitation to improve strength and endurance. The suit is in 25 physical therapy locations worldwide and costs $140,000. The suit has seen much promise, and the Kessler Foundation has reported that there might be an increase in strength and endurance after using the suit. [5]

Also exciting is the work being done with the MIT Manus physical therapy robots. Through their years of research, studies have shown that robotic therapy facilitates motor recovery following stroke, with the belief that it promotes brain plasticity. Their robotics have been applied to the shoulder, elbow, ankle, hand, and wrist. Their studies have shown that there muscle improvement has doubled with the use of assistive robotics. [6]

The University of Tokyo has completed significant development in the field of upper body exoskeletons, using powered air muscles and a metal frame to mimic the human musculoskeletal structure. Their suit enables the ability to hold large static loads of about fifty kilograms. [7]

Though there are existing methods for treating physical therapy through human or robotic physicians, we believe that there is a need for a mobile, at-home solution for physical therapy, capable of instructing the patient and tracking improvement over time. In addition, the addition of extra lifting capability could be used as a preventative measure in the workplace to avoid injuries. For example, overexertion was the number one most disabling work injury in 2009, resulting in a total cost of $12.5 billion in lost days of work. [8]

Design

Titan Arm was designed to provide a safe, empowering, lightweight platform that will help weakened and elderly individuals regain their mobility and independence. To achieve this, we have designed and manufactured a tetherless upper-body exoskeleton which closely mimics the human range of motion while augmenting the user's strength. The suit, as seen in Figure 1, consists of three distinct subsystems: structure, actuation, and electronics. The structure is all of the components that attach to the user, provide load bearing strength, and ensure controlled motion. The actuation subsystem encompasses all of the parts which transmit power and strength to the user. The electronics system governs everything by reading, controlling, and communicating with the sensors, motors, and base station.

Figure 1: Completed Titan Arm exoskeleton

While developing the suit, the safety of the user has been a central focus of our design. By incorporating both software and mechanical protection mechanisms, we have created a suit that protects patients who are already injured or disabled. By continually reading the angle and movement of the user's arm, we are able to sense whenever a user is approaching the limits of human physiology. In such circumstances, software-based stops will halt the motor, regardless of user input. As a redundant failsafe, we have also incorporated mechanical stops into the actuated joint; stainless steel rods prevent both either extension or flexion of the elbow. We also are able to read real-time current data from our motor, allowing us to judge the output of the exoskeleton. By looking for unexpected loading patterns (such as reaching the mechanical stops), we can intelligently shut down the motor before any harm befalls the user or the exoskeleton itself. On top of all of these measures, we have incorporated an easy to use emergency shutoff switch on the controller, allowing the user to completely halt and slacken the motors if they become uncomfortable. Realizing how powerful our system is, we have purposefully designed a multi-tiered safety system to protect our users.

We have strived to create a system which offers innovative and useful features to all of our potential stakeholders, including disabled or injured patients, therapists, and doctors. To accomplish this, we have developed an exoskeleton that utilizes novel mechanical features such as a custom 3 degree of freedom (DoF) joint, non-localized actuation via a unique cable drive, and a ratchet-based braking system for static loads. The shoulder joint was specially designed to improve the overall functionality of the suit by allowing a fuller, more natural range of motion than competitor exoskeletons. We accomplished this via three self-designed and manufactured aluminum members, and assembled them with a complex series of bearings to produce smooth biomimetic motion while providing the strength necessary to augment human strength.

Our self-designed cable drive system allowed the suit's motor to be mounted on the user's back, instead of attaching directly to the actuated joint. This non-localized actuation system was especially novel, as it allowed us to use a more powerful motor, enabling greater lifting strength for the user. This method also produces a more mobile exoskeleton, as the centrally located motor is less bulky than arm-mounted designs. To transmit this force, the flexible cable drive provides the strength that users need while allowing unimpeded motion throughout the human range of motion. Non-localized actuation allows disabled persons to regain their former strength and flexibility without sacrificing mobility.

The ratchet-based braking system is a unidirectional locking system which allows users to lift and hold large loads. By using a DC motor as our actuator, we were able to ensure a safe, reliable suit with an impressive power-to-weight ratio over 180 W/kg. However, DC motors are unable to hold a static load without risking permanent damage; the braking system (shown in Figure 2) takes over in such situations. This innovative system is lightweight, compact, and requires very little power for operation, resulting in a more usable suit which operates for longer per charge. This would enable users to remain empowered in a home or work setting for longer.

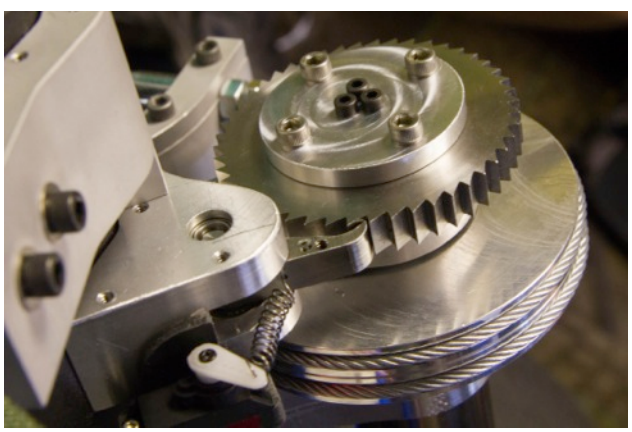

Figure 2: The braking system utilizes a pawl and ratchet system

The electronics system takes input from the user through a handheld controller. This is similar to that which is used in the Ekso Bionics lower body exoskeleton, and allows the user or a therapist to control the arm. A joystick controls the up and down velocity of the arm and a switch controls the activation of the ratchet braking system. A velocity-based controller takes the input from the joystick and maps it to the output signal sent to the motor, smoothing the motion of the arm in the process. A main microcomputer runs the overall control loop, taking in sensor data from each joint and controller input, and sending out commands to the motor.

In order to further improve the physical therapy applications of the suit, we have developed real-time joint tracking, which can be streamed to a therapist for further analysis. Using Hall Effect sensors on each joint, as well as current sensing on the motor, we are able to derive position, velocity, and acceleration data on the user's joints. By wirelessly streaming this data to a computer, this information can be sent to doctors or therapists for remote viewing. Using this data, professionals can track user improvement over time, providing demonstrative proof that disabled or injured individuals are healing. This improves user morale, and encourages them to keep pushing forward to heal faster. This data offers both users and therapists a vastly improved, quantitative physical therapy experience. Additionally, this data provides the information necessary to show that our exoskeleton is making a real difference in patient progress, which is absolutely necessary to convince insurance companies to help defray the cost of our system for hospitals and patients.

Conclusion & Evidence of Working Prototype

Our upper body exoskeleton was successful at completing all of our predefined metrics, which we developed at the outset of the project nine months ago. The Titan Arm has a low-inertia arm, with the majority of the weight being attached to the back-plate. The low-inertia arm reduces the stress of added weight at the extremities of the user's body, and also increases the total amount the suit is capable of lifting. Non-localized joint control was achieved by using a novel cable drive system, with two pull-pull configured spools located at the motor and elbow. Together, these innovations allow Titan Arm to augment a user's lifting strength by up to 40 lbs. One of our teammates can be seen using the suit in Figure 3.

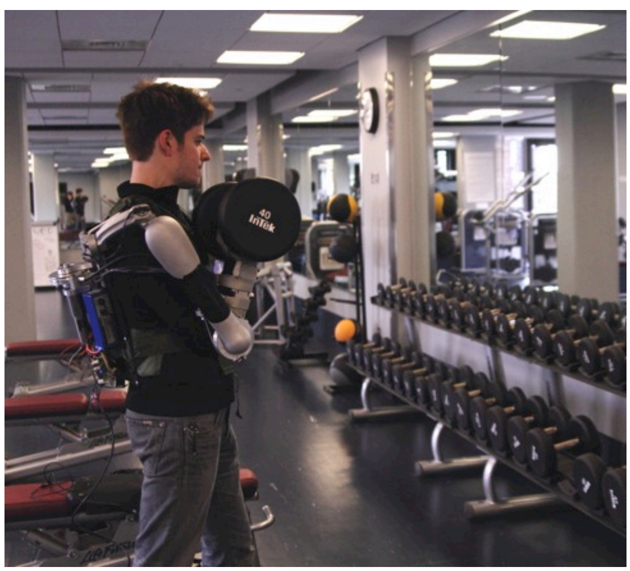

Fig. 3: Lifting weights with assistance from the exoskeletal suit.

The suit is completely untethered, capable of powered use and data transmission in a mobile fashion. The arm is also backdriveable, a condition necessary to help ensure the safety of the user at all times. Two lithium polymer batteries, rated at 5000 mAh, provide the high energy density required to power the suit intermittently for over twenty four hours in testing. The batteries give a high usage to charge time ratio as well, with just twenty minutes needed to safely recharge.

The entire suit was developed under $2000, with the component cost of the final suit at $1500. This low-cost exoskeleton is a promising conclusion for the expansion of physical therapy devices for the masses. The suit is also capable of expanding user strength up to an additional forty pounds on existing strength. The ratchet braking system allows the user to hold up to sixty pounds for extended periods of time, removing the load from both the user's muscle and the exoskeleton motor.

Data streaming was implemented using standard 2.4 GHz wireless technology and is capable of streaming to multiple users in concurrently in real-time. This data is logged and can be imported into a personalized user interface for patient tracking and doctor observance. By collecting data on joint angles and motor force, we have been able to visualize and analyze user range of motion and strength like that shown in Figure 4. We want to utilize this data to improve therapy, motivate patients, and empower people to regain their everyday lives.

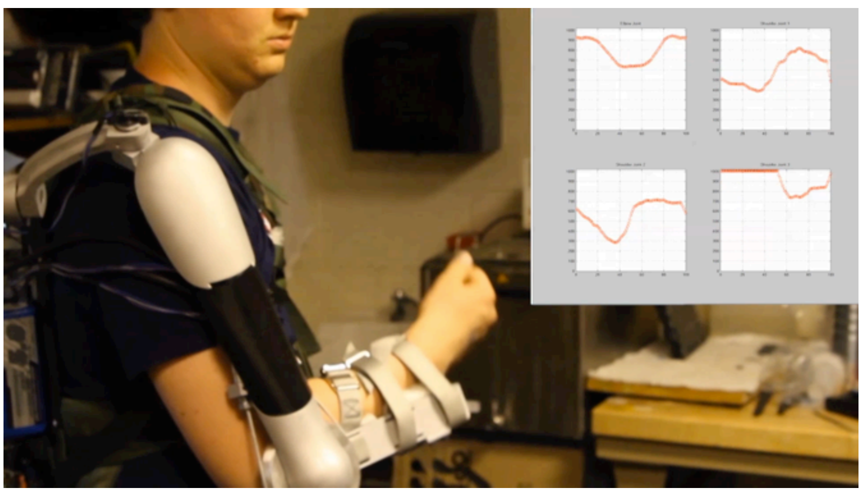

Fig. 4: Mapping joint angles from the suit in real-time.

Titan Arm is most valuable for its potential to improve the lives of millions of disabled or injured people around the world. From the beginning, we set out to create a device that could empower people, giving them the mobility and strength assistance they need while remaining ergonomic and easy to use. To that end, our proof of concept has hit every metric and milestone we've set. For the future, we want to expand by adding functionality, improving our design, and implementing new technologies that will truly allow people to regain their lost independence. For example, using technology like electromyography (EMG) sensing would allow the suit to read muscle activity – however weak – and translate that into suit movement. As a feedback loop for stroke patients, this would help exercise damaged limbs, aid in regenerative brain plasticity, and return people's lives to normal. Our team is excited to start bringing transformative robotics technology out of the laboratory and into the homes of patients worldwide.

References

[1] American Heart Association. 2003. Heart disease and stroke statistics. Web. 06 June 2013.

[2] Japan’s National Institute of Population and Social Security Research. Available: http://www.ipss.go.jp/index-e.html.

[3] Britt, Darice. "Physical Therapy Crucial to Sports Injury Recovery." *Physical Therapy Crucial to Sports Injury Recovery*. South Source, 1 Nov. 2011. Web. 06 June 2013.

[4] Morris, Meg E., and Peter Kempster. "Protocol for a Home-based Integrated Physical Therapy Program to Reduce Falls and Improve Mobility in People with Parkinson’s Disease." *BMC Neurol* (n.d.): n. pag. Web. 6 June 2013. <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3436761/>.

[5] Lapowsky, Issie. "Meet the Makers of the Wearable Robot." *Inc.com*. N.p., 30 Oct. 2012. Web. 06 June 2013.

[6] *Proc IEEE Inst Electr Electron Eng*. 2006 September 1; 94(9): 1727–1738. doi:10.1109/JPROC. 2006.880721.

[7] Lai, Richard. "Tokyo University of Science Shows off Robotic Suit Powered by Pneumatic Artificial Muscles (video) Hands-on." *Engadget*. N.p., 2 Oct. 2012. Web. 06 June 2013.

[8] "Pain in the Workplace." *In the Face of Pain*. Purdue Pharma, n.d. Web. 6 June 2013.