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A Bio-Robotic Leg Orthosis for Rehabilitation and Mobility Enhancement

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Abstract— **This paper describes a wearable powered leg orthosis that includes a high-torque actuator, electronics, sensors, and embedded firmware. The device provides multiple modes of operation including automatic assistance, manual assistance, continuous passive motion and robotic therapy. Patients affected by neurological conditions including stroke, MS, and Parkinson's disease may benefit from robotic therapy and from the improved mobility provided by this portable, lightweight device. A preliminary study of chronic stroke patients has shown retained improvement in walking speed for patients undergoing rehabilitation with the device.**

I. Introduction

THE availability of lower-limb active orthoses offers promising new technology for rehabilitation from conditions affecting mobility. In particular, those suffering from neurological conditions such as stroke, Multiple Sclerosis (MS) and Parkinson's disease can benefit from robotic therapy and improved mobility provided by portable, lightweight bio-robotic orthoses. This paper describes the engineering challenges and early patient feedback encountered in the development in the Tibion PK100 bionic leg orthosis.

II. Background

Recent research in neuroplasticity has shown the potential for new therapies to aide neurological conditions formerly thought to be untreatable [1]. New robotic therapy devices have demonstrated improvements in motor impairment in hemiparetic upper and lower limbs. Examples of these devices include the MIT-MANUS for upper-extremity robotic therapy [2,3] and the Active Leg Exoskeleton (ALEX) for robot-assisted gait training [4]. Research with these and other robotic therapy devices shows the potential for neural pathway retraining even in patients whose progress has reached a plateau several years post-stroke. While these devices show great promise, they have limitations stemming from the fact that they are stationary devices that must be tethered to the lab in order to provide the required power and control. If these devices were more portable, they could be more widely available and the patients could benefit from more frequent therapy sessions.

Another promising avenue of research is for portable devices to improve mobility. Some devices for lower limb impairment have a computer-controlled braking mechanism to support the patient and to provide controlled flexion [5,6]. While these devices provide benefits with controlled resistance, they are unable to augment weak quadriceps muscles to aide patients who have trouble rising from a chair or ascending steps. The braking devices also cannot provide walking assistance to help restore a natural gait. Some active devices have been developed, however these have primarily been prosthetic devices for above-the-knee amputees [7].

An active lower-limb orthosis combines the benefits of robotic therapy and mobility enhancement in a single, portable device. Therapy is enhanced by the improved mobility provided by the device, and the mobility enhancement is improved over devices that do not provide the force required to augment muscles that are weak or not well-controlled. The incentive for such a portable device has been clear to many researchers, but the technology to provide these features has awaited improvements in actuators, portable electronics, and supporting technologies. The PK100 has been designed to solve the difficult problems related to the design of light-weight, portable therapy and assistance devices.

III. Design Elements

Figure 1 shows the PK100 active knee orthosis. The orthosis is constructed of carbon fiber to provide the structure needed to transfer the high forces required for active assistance during sit-to-stand, stair ascent/descent, and walking. The active elements are located in a housing attached to the orthosis and positioned over the thigh. The housing supports and protects the actuator, motors, battery, electronics and user interface. The output of the actuator is coupled to the orthosis by a linkage, and the orthosis is coupled to the upper and lower leg via size-adjustable textiles. Fine adjustment of the textiles is provided to accommodate the patient needs for comfort and support. A foot sensor is inserted inside the shoe to provide the weight-on-foot information used in the control algorithms. Other sensors provide information about the knee angle, the force applied by the actuator, internal temperatures, motor currents, and battery voltage.

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Fig. 1. The Tibion® PK100 bionic leg orthosis

Figure 2 shows the location of the major elements inside the housing. The heart of the device is the actuator supplying the force to assist or resist leg extension and flexion. The design requirements of this actuator are extremely difficult to meet in a portable, battery powered device. The actuator must be capable of applying significant assistance for patients weighing 100 Kg or more. To provide assistance during normal ambulation, the actuator is required to provide a peak power of hundreds of watts. The actuator also has severe size and weight constraints to prevent the size from interfering with the normal movements of the patient.

Effective actuators for active knee orthoses require variable impedance to allow free movement of the leg in swing phase as well as variable assistance during the stance phase of gait. During swing phase, the drive train is completely decoupled from the orthosis to allow unencumbered movement to allow the leg to swing naturally. During stance phase or for other powered movements such as sit-to-stand, a variable ratio transmission provides the appropriate tradeoff between high force and high speed. The design has evolved through several generations of continuously variable transmissions [8,9] before arriving on a design that allows programmatic control of the ratio while

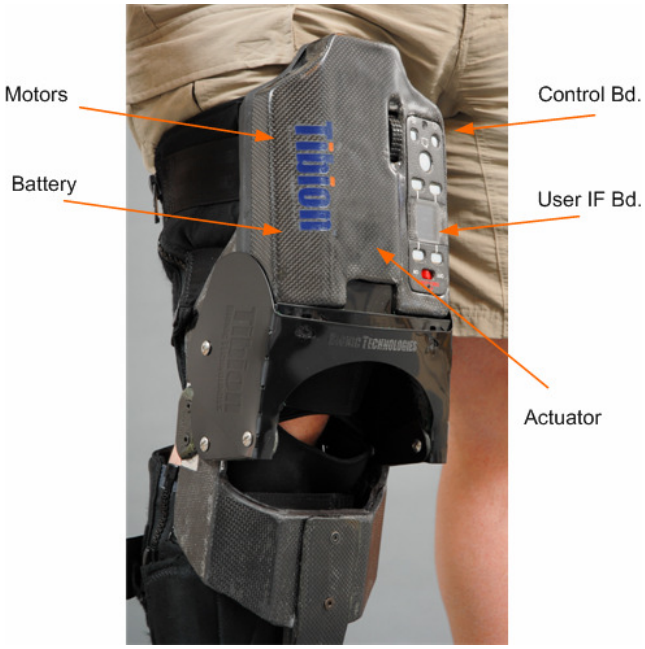

Fig. 2. Location of major components inside housing

allowing the use of small motors. The small motors are important both to keep the overall size of the device as small as possible, and to allow for simplified electronics with reasonable requirements for voltage and current. The motors operate off of high-current lithium-ion batteries.

Figure 3 is a block diagram of the electronics and sensor interfaces. The electronics is partitioned into two main boards for the control and the user interface. The control board includes the power electronics for switching power to the AC adapter and battery, a battery charger circuit and the DC power conversion. A Xilinx FPGA handles the real-time functions for motor phase generation and also includes the interfaces to the position encoders for knee angle and motor positions. A high precision analog-digital converter (ADC) converts inputs from a force sensor that gives an accurate reading of the current torque being applied by the actuator. Other sensors measure motor currents, voltages, and latch positions. An external Bluetooth adapter can provide access to the internal state of the device for configuration and recording of device operation parameters.

The user interface board includes a color 128x128 organic LED display, buttons, LEDs and a speaker for audio feedback. A menu-driven user interface allows configuration of device operation including range of motion limits, torque limits, and tuning parameters. Once the device is configured for a particular patient, little further interaction is required beyond selection of the desired mode of operation.

The electronics also has a connection to the foot sensor shown in Fig 4. The biomechanical algorithms make use of information from the force-sensitive resistors (FSRs) in the

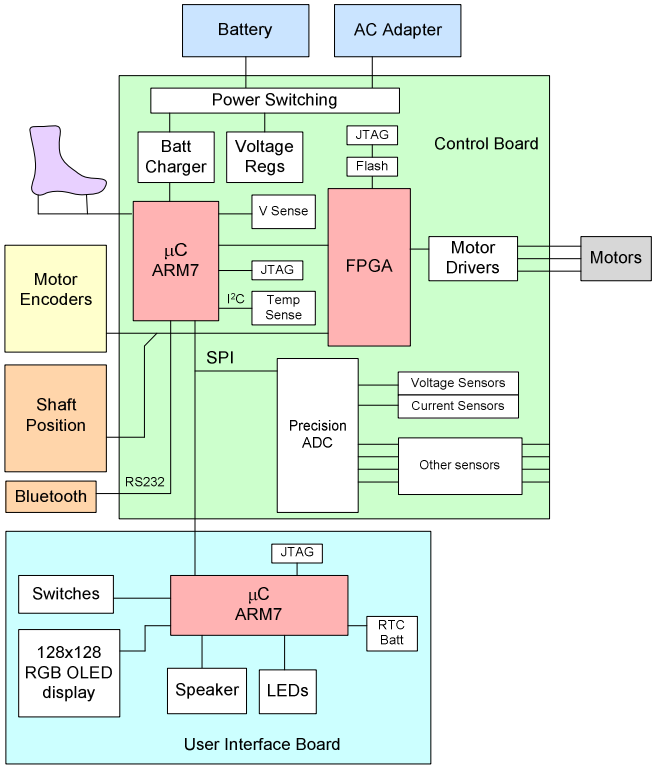

Fig. 3. Electronics and sensors.

foot sensor in order to determine when the patient requires extra assistance for sit-to-stand or stair ascent. The foot sensor includes redundancy to provide fault-tolerant operation to continue correct operation despite failures in connections or sensors.

The firmware is built around a real-time operating system and a scheduler that provides guaranteed levels of service to the time-critical tasks. The firmware is layered to allow adding higher level modules to add functionality for other conditions or rehabilitation protocols. Display and control processors implement a reliable communications protocol over a serial link. The control firmware also manages a log in flash memory for recording statistics, configuration information and one-time events.

IV. Device Operation

The PK100 user interface includes four firmware-controlled soft buttons plus buttons for standby/power, muting the speaker, and navigation to the home screen. A slide switch allows the user to cut all power from the device for shipping or emergency shutdown. A menu system can be used to customize certain parameters such as range of motion, amount of assistance and speed of therapy modes. Once the unit is configured, the patient only needs to select the desired mode of operation

The primary mode of operation is the AUTO mode in which the unit transparently activates to assist the motion made by the patient. The control algorithm uses inputs from the sensors and operation states to determine when to apply force. In this mode, when the actuator supplies force, it is always against gravity. In some cases, it applies force in the direction of movement, to assist in lifting the body during stair ascent, sit-to-stand, or for forward propulsion while walking. In other cases, the force is opposite to the direction of motion to provide controlled descent from stairs or stand-to-sit. In other cases, the actuator is decoupled to allow free movement during swing phase or while seated with no weight on the foot.

A manual mode may also be selected by the patient. This mode allows the patient to push a button to initiate sit-to-stand or controlled descent for stand-to-sit. Manual mode also includes a leg lock feature which is a low-power mode that holds the brace at full extension. This mode is useful for those needing support for standing for long periods of time or those who would otherwise need a stance-control brace.

The continuous passive motion (CPM) mode provides the ability for the PK100 to apply forces in both the extension and flexion directions for slow repetitive motion of the leg. This mode provides the CPM capability typically prescribed after knee surgery in order to regain range of motion and to reduce stiffness. CPM mode is engaged through the therapy menu and by rotating a knob on the housing that engages or disengages the actuator's ability to apply force in the extension direction.

Robotic therapy (RT) mode is a stationary therapy regimen, in which the motion is no longer purely passive; the sensors detect when the patient begins the motion and then when the motion can no longer be maintained. When the motion slows or cannot be completed, the actuator assists in completing a motion that would otherwise be unattainable. RT mode is typically used after a stroke to begin the neural retraining process. Once the patient gains enough control over the affected leg, the AUTO mode can be used for high frequency task-specific training to improve gait, to gain confidence, and to once again rely on the affected limb.

Fig. 4. Foot sensor with and ankle support

V. Early Patient Feedback

Patient tests of the PK100 are currently underway. Informal tests have been performed on patients with MS and Parkinson's disease, but the primary patient groups are those undergoing knee surgery and patients recovering from stroke.

A preliminary study with three post-stroke patients was recently completed at the UCSF Department of Physical Therapy and Rehabilitation Science. In this study, supervised by Prof. Nancy Byl, the patients received physical therapy with the PK100 several times a week for four weeks. At the end of the study, the patients were re-tested while not wearing the device and all three patients achieved significant improvements in walking speed. In a follow-up test a month later, the patients had retained the improvements in their walking speed. These results are believed to be quite significant given that two of the patients were several years post-stroke.

The feedback from other patient testing is also quite encouraging. Some patients who could not rise from a chair or sit without significantly shifting their weight were able to complete these tasks after training sessions with the device. Other stroke patients appear to be making progress in improved gait while wearing the device and are being evaluated to determine how much improvement is maintained after the device is removed. Future reports will provide more details on the progress of the trials.

VI. Conclusion

This paper has described a bio-robotic orthosis for assistance and rehabilitation. The design requirements required innovations in the actuator, electronics, firmware algorithms, and orthotics. It is our hope that this device is just the beginning of a new industry which will produce other bio-robotic devices for assistance and rehabilitation for a wide range of medical conditions.

Acknowledgment

The PK100 is the result of an intense, extended effort of a small but dedicated development team. The author wishes to acknowledge the key contributions of all of the team members who contributed to the concepts, implementation, and patient testing of this device.

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