Engineering Evaluation of the Energy-Storing Orthosis
FES Gait System
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Abstract—A system to restore walking in the vicinity of a wheelchair for people with paraplegia resulting from spinal cord injury is under development. The approach combines single channel surface electrical stimulation with an orthosis. The orthosis is spring loaded and contains a pneumatic system that stores energy during knee extension caused by quadriceps stimulation and transfers it to hip extension for knee. A laboratory version of the prototype of the gait system has been fabricated and engineering bench tests were performed. The paper presents the design of the wearable prototype and results of bench testing.

I. INTRODUCTION

Loss of motor function in lower extremities and the resulting loss of ambulatory function is a common result of thoracic level spinal cord injury (SCI) [1]. Among the various functions lost due to SCI, restoration of walking is considered important by clinicians and users [2-4]. Functional Electrical Stimulation (FES) has been used to restore mobility in some SCI individuals by electrical stimulation of peripheral nerves using low levels of current. FES is limited in its ability to restore mobility by two critical factors. First, stimulated contractions of the atrophied muscles cause rapid fatigue thus shortening standing and walking durations, and second, inadequate control of joint torques results in erratic limb trajectories and non-repeatable steps [5]. Hybrid systems address this problem by combining FES with an orthosis or external bracing system [6-10]. The orthosis concept presented in this paper was described by Rivard [11] and is based on earlier work by Goldfarb [12-13]. The preliminary design of the energy storing orthosis (ESO) system was described in [14]. The design requirements for the orthosis are listed in Table 1. This paper describes the design and presents results of engineering bench tests. Tests with human subjects will be reported later.

II. ENERGY STORING ORTHOSIS DESIGN

A. Functional Electrical Stimulation (FES)

The FES system for the ESO consists of a single channel uni-phasic, charged-balanced stimulation delivered via surface electrodes to quadriceps groups of muscles for knee stimulation of peripheral nerves using low levels of current. The orthosis is spring loaded and contains a pneumatic system that stores energy during knee extension caused by quadriceps stimulation and transfers it to hip extension for knee extension. Electrodes on each leg (2x4 in, Uni-Patch) are connected to an external stimulator carried in a backpack. One electrode is placed 6cm proximal to the knee cap while the second is placed on the upper thigh about 2 cm to the right of midline. The stimulator parameters are wirelessly controlled from an external laptop.

B. Structure

Fig.1 shows the laboratory version of the ESO. The total orthosis weight is 16.82 kg. The lateral width (from extreme left to extreme right) of the orthosis at the hip is 0.54 m and at the knee the brace projects 0.14 m on either side. The weight of the hip brace is 3.6 kg. The ESO system can be donned by individuals from 5’4” to 6’2” in height by adjusting two link lengths. The orthosis has four subsystems: trunk corset, hip brace, knee brace and reinforced ankle foot orthosis (AFO). The trunk corset (Rolyan AquaForm Corset, Sammons Preston) was shipped flat and was then fitted over a person of 6 feet height and given as generic shape as possible. The hip brace consists of a pelvic belt (Newport4, Orthomerica) on which are mounted the hip joints, pneumatic components and brakes. The knee brace consists of a modified commercial brace (Legend, Donjoy) which is attached to ankle foot orthosis (AFO). The trunk corset contains the AFO is reinforced with lateral steel rods and fixed in a shoe (Meron Canvas, Target) on which the sole of the shoe reinforced with a 1/16 in steel plate The joints are padded (Plastazote, Alimed) to eliminate pressure sores. The clamshell in the knee brace distributes the pressure at the cuffs and is molded from splinting material (Multiform Plastic, thin, Alimed) with the inside padded with foam (T-FOAM, non-adhesive, Alimed). Off-the-shelf components were selected to accelerate the design process because they are engineered
for aesthetics and functionality.

The remaining orthosis structure is fabricated from 6061-T6 aluminum and low carbon steel. Aluminum was chosen for its high strength to weight ratio. Steel was chosen where strength to volume ratio was more important. The spring for the wrap-spring brake is fabricated from high strength music wire. The four piece orthosis simplifies the process of putting on and taking off the apparatus.

**C. Energy Storage Design**

Two factors influenced the selection of a pneumatic energy storing system for the ESO application. First pneumatics have high energy/weight ratio and second, they do not require a mechanical transmission to transfer energy from the knee to the hip joint. The pneumatic circuit (Figs. 2 and 3) was designed to make the knee cylinder dead volume a part of the accumulator. Using the dead volume of the knee cylinder as part of the accumulator reduces the problem of energy loss reported in Rivard [11]. The pneumatic circuit uses a single 3/2 solenoid actuated spring offset directional valve (EV0 3-6, Clippard). Teflon tubing (5239K23, McMaster) and the knee cylinder (172-DP, Bimba) dead volume act as an accumulator. The knee cylinder is connected to atmosphere through a check valve when backstroking.

**D. Rubber Bands as Elastic Elements**

The rubber band is remarkable in two characteristics: its ability to store energy in a package that is small and light, and its ability to stretch many times its original length. The volumetric and mass energy density and maximum strain for rubber bands far exceed those metrics in metal springs. Rubber bands have other advantages. Flexion equilibrium position can be adjusted by adding or removing a few rubber bands. Rubber bands come in various sizes and do not have fixed extension lengths, thus providing flexibility in mounting locations.

**E. Optimizing Mounting Locations**

The objective of optimizing the location of the cylinders and rubber bands was to maximize the energy stored in the pneumatic system while operating within volume limits. There were two important criteria. First, the energy required to pull the legs into their flexed equilibrium position is minimized under quasi-static conditions if the rubber bands exert minimal torques through the range of motion. Second, the torque exerted by the rubber bands, knee cylinder and leg weight cannot be more than the torque generated by stimulated quadriceps. Optimal mounting points were found through simulations and the result was that the estimated energy stored in the ESO increased from the 5.1 J reported in [11] to 8.9 J. The increased stored energy leads to increased applied torque at the hip joint, thus providing more assistance for forward progression.

**F. Joint Brakes**

Wrap spring brakes were used to lock and unlock the hip and knee joints because wrap spring mechanisms have high holding torque to weight and high holding torque to operating energy. Wrap springs have exceptional gripping torque in the locking direction and low over-running torque in the reverse direction. Since wrap spring brakes are high torque low speed devices, they do not need transmission in the orthosis and can be directly coupled to joints. Wrap springs are failsafe (normally locked) so that in case of power failure the user will not collapse. The brakes were designed for 40 Nm torque based on earlier work [16] with the goal of minimizing their volume and weight. The final design resulted in a reduction of the lateral width of the orthosis by 4 in as compared to the CBO [12].

**G. Joint Design**

Because pin joints are light weight, easy to integrate with additional components and less susceptible to misalignment with the anatomical knee joint, the polycentric gears on the knee brace used for the ESO were removed and replaced with custom pin joints. On the lateral side, the pin joint is within the brake. In flexion, both hip and knee joint require extended range of motion for sitting but the pneumatic cylinders act as hard stops, preventing the extended ROM required for sitting. In addition, the rubber bands and the pneumatic energy storage system both urge the knee towards flexion, which hinders a sit to stand maneuver. Because of this, the pneumatic cylinders and the rubber bands are mounted on a disk which in turn is mounted to the wrap spring brake shaft but through thumb screws (Fig. 4). When the thumb screws are removed the cylinders and rubber bands are decoupled from the orthosis enabling sitting. Once the subject is standing, the components are coupled by fixing the thumb screws. The joints also incorporate a telescoping link between the knee and hip sections to accommodate persons of different size and to accommodate for any misalignment between the orthosis joints and the anatomical joints.

**H. Sensors, Electronics, Software and Control**

The ESO has open loop control but is equipped with sensors and related electronics for future development of closed loop control (Fig. 5). Heel strike and toe off events are detected by a foot sensing system (Flexiforce sensors, Tekscan). Strain gauges (SGT-2H/350-SY43, Omega) were placed on load bearing members to measure hip and knee torque of each limb. Potentiometers (LCP12Y-100, ETI) attached to knee cylinders and position sensing hip cylinders (PFC-092-XL) measure cylinder stroke which is used to estimate joint angle. The pneumatic pressure is measured using a pressure sensor (PX40-100G5V, Omega). The wrap spring brakes are controlled by pulse width modulation controlled solenoids (195206-224, Ledex). Each joint is controlled by a microcontroller on a printed circuit board mounted near the joint. These four boards communicate over USB to a netbook contained in the controller backpack worn by the subject. The netbook communicates wireless with a host computer over a Bluetooth link. The netbook handles all timing, local control, and data logging while the host computer displays input data, controls the timing of a step and sends commands to the remote devices. The step cycle control is
an open loop sequence of events where the event timing can be adjusted to optimize walking.

III. BENCH TEST RESULTS

The wrap spring brake (WSB) locks at 60 Nm – exceeding the design target of 40 Nm - with 6 deg of slip. For consistent performance the average power consumption by solenoid was 0.66 W. With the torque to power ratio of 60 Nm/W, and a torque to weight ratio of 100 Nm/kg, the WSB was confirmed to be suited for an orthosis application.

The pneumatic system was designed for 1.62 inches of knee cylinder stroke and 71.6 in. of accumulator tubing and was predicted to store 10 J of energy at a pressure of 90 psig. Because the knee extension was expected be slow, the air compression process was assumed to be isothermal. The actual stroke of the knee cylinder turned out to be 1.55 in and the pneumatic system was only able to store 9.6 J of air at a pressure of 67 psig. The drop in pressure from the ideal was attributed to the knee piston being unable to complete its stroke due to the bending in the brace’s structure. Any further rotation of the knee joint resulted in the brace being progressively deformed with the pressure remaining constant at 67 psig. The brace structure, however, rebounds as the pressure in the accumulator drops during hip extension allowing the knee cylinder to complete its stroke. The black line in Fig. 5 shows knee extension taking place during hip extension. Thus the missing energy in the accumulator is stored in flexing the brace structure. The increasing cylinder stroke during hip extension causes the observed hip pressure to rise above the theoretical curve (Fig 6). The observed pressure follows the same trend as the theoretical curve plotted with dead volume validating the experimentally calculated dead volume. The dead volume causes the accumulator pressure to drop from 67 psi to 52 psi when the valve opens by adding the hip cylinder dead volume to accumulator volume. During this process air freely expands without doing any work. Because of the free expansion, the compressed air does not lose any energy but does drop in pressure making it less useful for moving the hip. At the end of the hip cylinder stroke, the air pressure is 10.5 psig due to the difference in displaced volumes between the knee and the hip cylinder. When the valve changes state the air distal to the valve, compressed to 10.5 psig, is lost to atmosphere. The accumulator, however, retains most of the air at 10.5 psi which then aids in knee cylinder retraction during flexion. The estimated energy requirement of the fabricated system was found to be 20.1 J as compared to the predicted 15 J (Fig. 7). The excess energy requirement is attributed to high friction in the cylinder and the knee joint and higher rubber band forces than predicted.

IV. PRE-CLINICAL EVALUATION

A single 51 yr old male with a T12 spinal cord injury, approximately 9 years post injury with complete sensory and motor loss was used to test the ESO for fit and for standing. The subject was able to stand erect (Fig. 8) and recorded vitals showed that standing was effortless. The measured brake torque was within design limits. The subject described the brace as comfortable and the carefully located padding distributed the pressure evenly preventing pressure sores.

V. DISCUSSION

The bench test results of the ESO continue to demonstrate that the design is feasible. The fabricated system requires more energy to be stored than the designed system but by keeping the stored energy at a high pressure, this should not impact the ability to move the hip. The rubber band torque can be optimized for a particular individual by selecting appropriate number of bands. Pre-clinical evaluations have confirmed that the brace is sturdy, comfortable and failsafe and that it can be used safely in clinical testing.

REFERENCES


Figure 1: Laboratory version of the ESO worn by an able bodied individual.

Figure 2: Pneumatic circuit.

Figure 3: Accumulator volume.

Figure 4: Hip joint design.

Figure 5: Knee cylinder pressure-stroke: Comparison between measurements on and off the brace.

Figure 6: Hip cylinder pressure-stroke relationship: Comparison between measurements on and off the brace.

Figure 7: Energy distribution in the system.

Figure 8: Paraplegic subject standing with the aid of the ESO system.