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Single Channel Hybrid FES Gait System Using an Energy Storing Orthosis: Preliminary Design

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***Abstract*—A new system for paraplegic gait by electrical stimulation is presented. The system combines electrical stimulation of the paralyzed quadriceps muscle with a hip-knee orthosis. The orthosis is spring-loaded and contains pneumatic components that store and transfer the energy from knee extension caused by quadriceps stimulation to a pneumatic actuator that drives hip motion. In this manner, cyclic hip and knee motion with arbitrary timing can be achieved using a single channel of surface stimulation. Previous work developed a dynamic model and bench top prototype of the energy storing system. Simulation and design prototypes are presented with the eventual goal of developing a wearable version of the complete gait system.**

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). The incidence of SCI in US is 40 cases per million population or about 12000 new cases every year. Among these about 18.5% have incomplete paraplegia and 23% have complete paraplegia i.e. lesions in the thoracic, lumbar, or sacral regions of the spinal cord [1]. For individuals with SCI, the wheelchair is the primary tool used for mobility. Functional electrical Stimulation (FES) is one means to enable rudimentary gait in individuals with paraplegia and uses low levels of current to stimulate peripheral nerves [2, 3]. Even with FES, users require considerable trunk control and upper body effort to walk [4, 5]. Nevertheless, FES systems which enable standing and walking near a wheelchair provide individuals with paraplegia an option for mobility [6]. The objective of this research is to develop a mobility aid for persons with paraplegia caused by spinal cord injury that combines functional electrical stimulation (FES) with a unique, energy storing orthosis (ESO). The aims of the project are to design the hardware, software and control system, to conduct bench tests to evaluate technical feasibility; to design a wearable prototype and to conduct clinical trials with a small number of subjects.

A. Energy Storing Orthosis

The energy storing orthosis (ESO) concept was described by Rivard [7] and is based on earlier work by Goldfarb [8,9]. To achieve the goal of using only single channel of stimulation, FES is combined with a mechanical orthosis with energy storage. A simplified gait cycle requires flexion and extension of the knee, and flexion and extension of the hip. By stimulating quadriceps, only knee extension can be achieved. But part of the energy during knee extension, is stored in the system and released at appropriate times to complete the gait cycle. In the ESO, excess energy generated by stimulating the muscle is stored during one part of the cycle and then released in another part of the cycle to achieve a complete step (Figure 1).

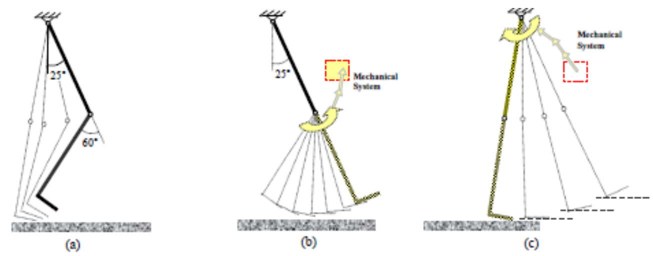

Fig. 1. The gait cycle starts with the system being in the equilibrium position as shown in (a). The brace is held in equilibrium position by elastic storage elements. In fig (b) the quadriceps are stimulated and the knee extends storing energy in the fluid power system. Simultaneously energy is also stored in the elastic storage element at the knee joint. In fig (c) the knee is locked, energy is releases into the hip actuator and hip extends enabling forward progression and storing energy in the hip elastic storage element. At the end of forward progression the elastic storage elements pull the leg back to equilibrium position and the cycle is completed.

A realization of the ESO is shown in schematic form in Figure 2. Gas springs act as elastic storage elements on the knee and hip joint. Pneumatic cylinders on the hip and knee joint along with the valves and the tubing forms the energy storage system. The pneumatic cylinder at the knee acts as the compressor, compressing air and storing energy in the tubing between two cylinders which acts as the accumulator. The accumulator has solenoid valves at each end. Compressed air is released from the accumulator into the hip cylinder which acts as the hip actuator, aiding forward progression. A pneumatic system has the advantage of very light, compact components and the ability to transfer power via flexible tubes from one joint to the other. Further, control of the system with electrically actuated air valves is simple and direct. Instead of gas springs, the current version of the ESO uses elastic bands made from natural rubber for a significant weight savings.

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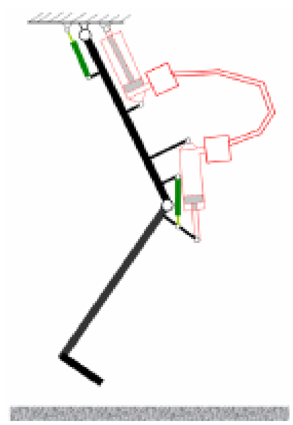

Fig. 2. Realization of ESO using pneumatic pistons and gas springs at knee and hip.

Rivard implemented a simplified dynamic simulation model of the system using MSC ADAMS, determined the optimal locations for the cylinders and gas springs and verified that the ESO concept was viable for an average male with height 70 in. and weight 168 lbs. [7]. The model assumed that 14 J could be extracted from the quadriceps at every step, with 5.1 J going to the accumulator as stored energy. A physical model was realized by mounting components onto a wooden model of the leg that matched the weight and inertia properties of a real leg. Results from the physical model matched the dynamic simulation model with reasonable accuracy. Additional optimization adjusted the mounting locations to minimize size and weight of the joint while retaining suitable torque-angle properties of the pistons and elastic band springs.

II. Wearable Orthosis Design Description

A. Overview

Using the simulation and physical model results to drive the design, a wearable ESO is being developed. Figure 3 shows a rendering of one version of the system. The power transmission components are mounted on commercial orthotics, the Newport 4 Hip System belt and the Donjoy Legend knee brace.

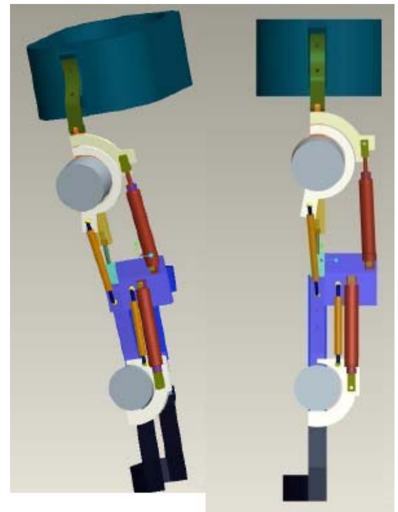

Fig. 3. Rendering of wearable ESO.

B. Joint Brakes

The ESO requires a computer controlled brake to lock the hip and knee joints during stance and during specific parts of swing. Specifically, the brakes: (1) Hold knee in extended position while the hip extension starts. If not locked, the compressed air would push onto the knee piston and undergo knee flexion. (2) Provide stance phase control to prevent collapse. (3) Control knee and hip trajectory during extension/flexion.

To specify the joint brake, it was necessary to estimate the required braking torque. Because the highest torque requirement would be from stance phase control where the entire body weight acts, this condition was used to set the torque requirements. A Matlab script was developed to model the variations in torque with posture. Hip and knee joints were modeled as pin joints. The subject was assumed to be 70 in. tall with a weight of 168 lbs. The foot was assumed to be fixed to the ground and the condition for stability was that center of gravity would pass through the center of the foot. Using this condition, different stable configurations were obtained and the torque acting at the hip and knee joint was calculated as shown in Figure 4. From these results, it was determined that the required braking torque for stance phase control was 50 Nm.

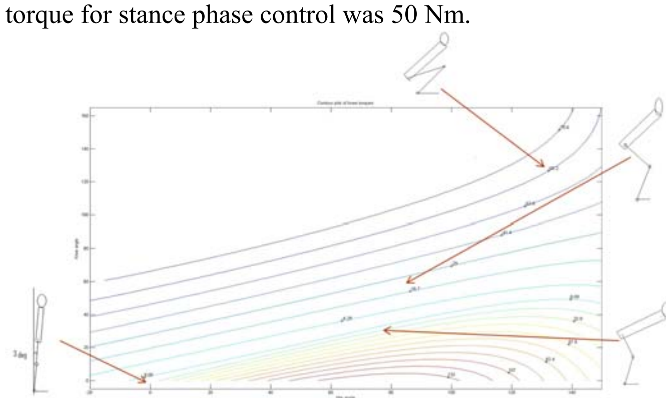

Fig. 4. Joint torques at various postures.

A wrap spring brake is a device used for start-stop braking and consists of an input hub, output hub and a close wound helical spring [10]. In a normally locked design of a wrap spring brake, the diameter of the spring is slightly less than the diameter of the hubs. The spring is fitted on the two hubs which are placed adjacent to each other, thus its diameter increases and it tightly grips the two hubs preventing any relative motion. To unlock the brake, a solenoid is used to pull on the end tang of the spring that uncoils the spring slightly thus freeing the hubs.

To design an optimum wrap spring brake for ESO, a Matlab model was developed based on design equations by Weibusch [10], Burr [11], Irby [12], Merz [13] and Kaplan [14,15]. The equations for the gripping torque in gripping and over running directions are

$$T_g = EIR\frac{\left(r-r_0\right)}{r_0 r^2}\left(e^{2\pi N\mu}-1\right)$$

$$T_o = EIR\frac{\left(r-r_0\right)}{r_0 r^2}\left(1-e^{2\pi N\mu}\right)$$

The objective of the optimization process was to have a brake of minimum volume (least axial width and least radius) and hence weight. Since these dimensions also depend on the spring dimensions, bounds were set on the spring dimensions. The spring dimensions can be bounded by the power requirement of the solenoid required to disengage the brake. A study of commercial solenoids suggested that the force to release the spring should be less than 10 N. A least-squares optimization was performed, minimizing the merit function

$$M = \left(\frac{L}{L_{\max}}\right)^2 + \left(\frac{R}{R_{\max}}\right)^2 + \left(\frac{F_s}{F_{s\max}}\right)^2$$

with each parameter normalized to a reasonable upper bound.

An incremental search was used to determine the optimum solution. Thickness (radial height) of the spring wire and radius of the hub were kept as variables. Length L, number of coils N, width b and spring actuation force Fs were calculated for each combination of thickness and radius. For each solution, which had acceptable values as determined by bounds on L, N and Fs, the merit function was evaluated. The set of parameter values that had lowest merit function was declared as optimum solution for the wrap spring brake design. Figure 5 is a rendering of the optimized wrap spring brake design.

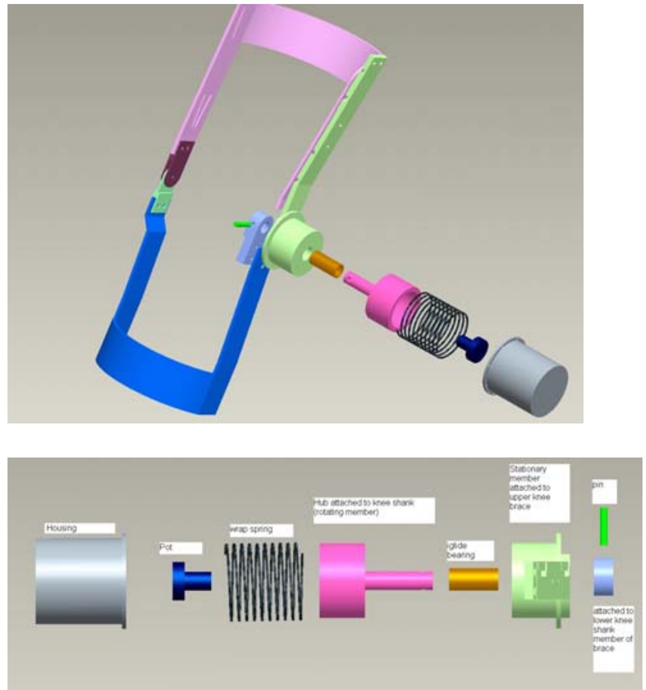

Fig. 5. Wrap spring brake design.

A. Pneumatic Control System

A hydraulic system with a piston accumulator to store and transfer power between the knee and the hip was considered. Analytical and experimental results quickly confirmed that the energy per cycle lost to flow losses across the valve (Enfield LS V05 proportional valve running Lubritherm All-Temp Hydraulic Fluid) would be unacceptably high. Of the 5.4 J that was stored in the accumulator, 5.0 J would be lost across the valve leaving too little to drive the hip cylinder. Therefore, an all-pneumatic system was determined to be the only acceptable design solution. Pneumatics has the added advantages of exhausting to atmosphere eliminating the need for a reservoir and being clean so that leaks do not matter, unlike with oil based hydraulics.

The pneumatic circuit is shown in Figure 6. A two-way proportional valve (Clippard Minimatic) was used at the knee to meter the amount of air entering the accumulator and to control knee extension while a three-way proportional valve was used at the hip.

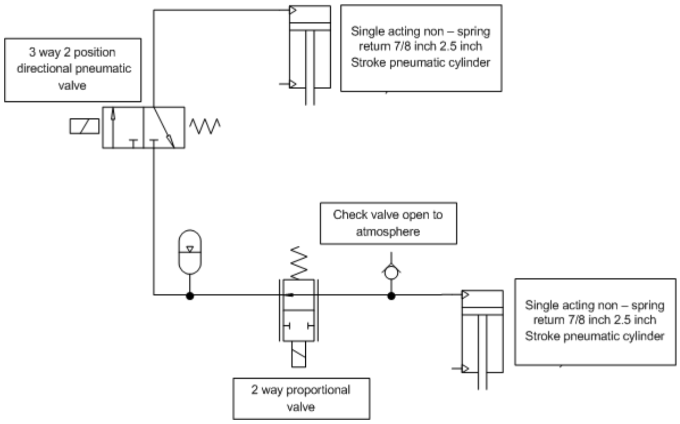

Fig. 6. Pneumatic circuit.

III. DISCUSSION

The preliminary design of the ESO continues to demonstrate that the technical approach is feasible. Considerable design details remain to fully realize a wearable ESO prototype. Beyond the prototype, for commercial realization, attention must be paid to minimizing size, weight and ease of use of the orthosis.

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