Design of a Joint-Coupled Orthosis for FES-Aided Gait

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***Abstract*—A hybrid functional electrical stimulation (FES)/orthosis system is being developed which combines two channels of (surface-electrode-based) electrical stimulation with a computer-controlled orthosis for the purpose of restoring gait to spinal cord injured (SCI) individuals (albeit with a stability aid, such as a walker). The orthosis is an energetically passive, controllable device which 1) unidirectionally couples hip to knee flexion; 2) aids hip and knee flexion with a spring assist; and 3) incorporates sensors and modulated friction brakes, which are used in conjunction with electrical stimulation for the feedback control of joint (and therefore limb) trajectories. This paper describes the hybrid FES approach and the design of the joint coupled orthosis. Preliminary experiments are presented which test the joint coupling concept and assess the extent of quadriceps fatigue imposed by the bias spring and joint coupling.**

I. Introduction

PREVIOUS studies have demonstrated that functional electrical stimulation (FES) can effectively restore legged mobility to spinal cord injured (SCI) individuals (with the help of a stability aid), and that such legged mobility can provide significant physiological and psychological benefits to SCI users [1-18]. Despite this, two significant factors have hindered FES-aided gait systems from restoring gait to SCI individuals. The first is the rapid muscle fatigue that results from artificially stimulated muscle contraction [19], and the second is the inadequate control of joint torques necessary to produce reliable and repeatable limb motion and body support. The former (which significantly influences the latter), is due primarily to the synchronous nature in which artificial stimulation recruits motor units (i.e., is due to lack of neural specificity in the stimulation interface). The net effect is that, when stimulated at a high level of effort and high duty cycle, the muscle quickly (i.e., over tens of seconds) loses its ability to generate force [12]. Both issues (rapid onset of fatigue and poor controllability) can potentially result in collapse of the individual, a condition that is unacceptable in any viable gait restoration system. Additionally, FES-aided gait systems (and especially surface-based systems) generally provide stimulation for degrees of freedom in the sagittal plane, but do not provide control over several other degrees-of-freedom associated with gait, such as hip abduction and adduction in the frontal plane. A lack of control authority in this plane can result in one foot crossing in front of the other (i.e., scissoring), which is a condition that is not easily rectified by the user (i.e., is likely to require external assistance).

Due primarily to these challenges (i.e., the potential of collapse from muscle fatigue and the need to guide uncontrolled degrees of freedom), hybrid systems, which combine FES with an orthosis, appear to offer the greatest promise for commercially viable gait restoration systems. As such, recent efforts by various researchers have focused (and are focusing) on the development of hybrid systems (e.g., [20-23]). This paper describes a hybrid FES approach that utilizes surface stimulation of only the quadriceps muscle group of each leg, along with an energetically passive, controllable orthosis (see Fig. 1) which 1) unidirectionally couples hip to knee flexion; 2) aids hip and knee flexion with a spring assist; and 3) incorporates sensors and modulated friction brakes, which are used in conjunction with electrical stimulation for the feedback control of joint (and therefore limb) trajectories.

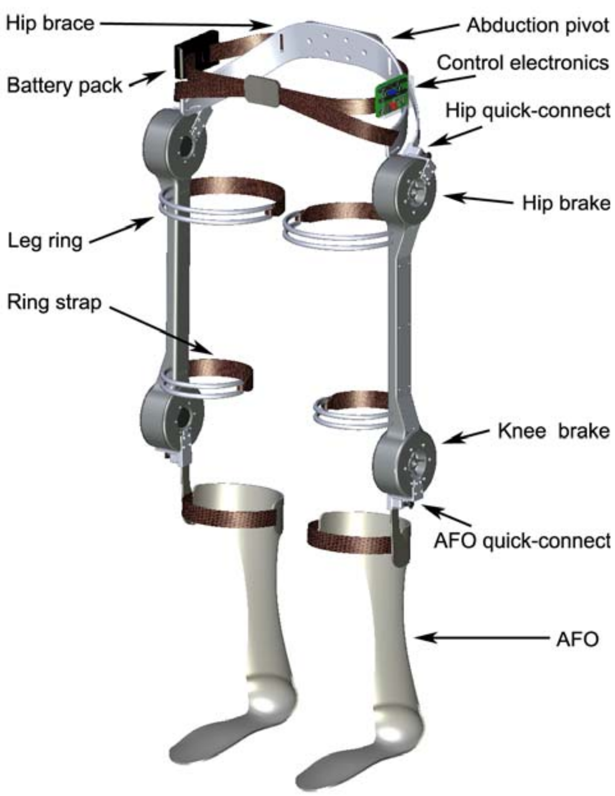

Fig. 1. Solid model of JCO concept.

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II. Joint-Coupled Controlled-Brake Orthosis (JCO)

The authors are developing a joint-coupled controlled brake orthosis (JCO) for regulating FES-aided gait. The JCO incorporates multiple features, which serve multiple functions. First, the JCO incorporates unidirectional joint coupling between knee and hip flexion, such that knee flexion generates hip flexion. Since the coupling is unidirectional, however, knee extension does not generate hip extension. The JCO also includes a biasing spring, such that the knee joint (and due to coupling, also the hip joint) is biased toward an equilibrium position in which both the knee joint and the hip joint are flexed. The combination of the (unidirectional) joint coupling and the biasing spring enables knee flexion, hip flexion, and knee extension, all from surface stimulation of only the quadriceps muscle group of each leg. The quadriceps muscle group is among the most powerful and easiest (in the lower limb) to access via surface stimulation, and thus provides a convenient source of metabolic power for gait. In addition to the joint coupling and biasing spring, the JCO incorporates controllable friction brakes at both knees and hips, which can either independently lock these joints (i.e., to provide for "isometric" muscle contraction), or can modulate the resistive torque at each joint for purposes of controlling limb motion. The JCO also contains angle (and thus also angular velocity) sensing at both hips and knee, which provide essential information for purposes of feedback control of limb motion. Finally, the JCO constrains motion along uncontrolled degrees-of-freedom (e.g., ankle flexion and hip adduction) which enhances the controllability and stability of gait.

A. The JCO Gait Sequence

The gait control approach is described subsequently in the section on gait control and simulation, but is described briefly here to motivate the design of the JCO. Postural stability during gait is provided by a stability aid, such as a walker (see Fig. 2). The knee of each leg is locked by the controllable friction brakes during stance (see Fig. 3). Swing is initiated by unlocking the swing leg knee brake, which releases the energy in the biasing spring, which flexes the knee joint and (due to the joint coupling) also flexes the hip joint. During the second half of the swing phase, the hip is locked by the hip brake while the knee is extended by stimulating the quadriceps group. This knee extension (due to stimulation of the quadriceps) does not, however, generate ipsilateral hip extension, since the (cable-based) coupling is unidirectional. Once the knee is fully extended, it remains locked (by the knee brake) during the stance phase of gait.

B. Joint Coupling Design

The purpose of the joint coupling is to provide hip flexion necessary to generate forward leg motion, which is otherwise a challenge, due to the inaccessibility of the deep hip flexor muscles via surface stimulation. The JCO design incorporates a Bowden cable which spans the inside of the femur link and attaches to the hip and knee rotors on either end (see Fig. 4). Cable compression sleeves are used in the hip brake as hard stops in only one direction of rotation, which provides unidirectional coupling of knee flexion to hip flexion. During knee extension, the distal end of the inner Bowden cable winds around the inner hip brake rotor without inducing concurrent hip extension (see Fig. 4d).

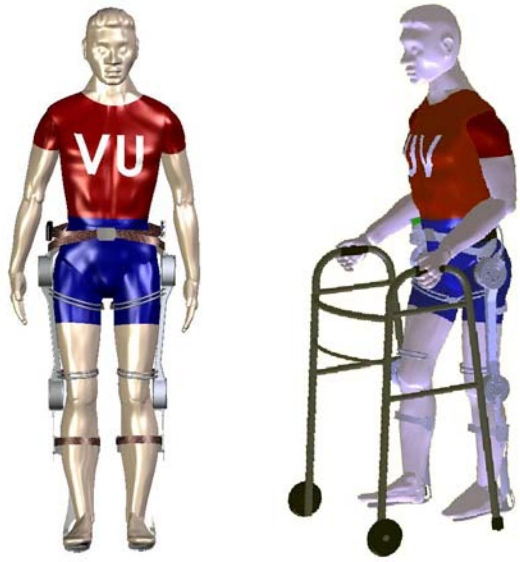

Fig. 2. Anthropomorphic 50th percentile male with JCO and with walker for stability aid.

As previously mentioned, the power for knee (and therefore hip) flexion is provided by the quadriceps, but is stored in an extension spring housed within the femur tube (see Fig. 5). This spring is attached to the returning end of the Bowden cable which is wrapped around the knee brake rotor, thus creating a torque in the direction of knee flexion as determined by the spring stiffness, equilibrium point, and preload (against a joint hard stop).

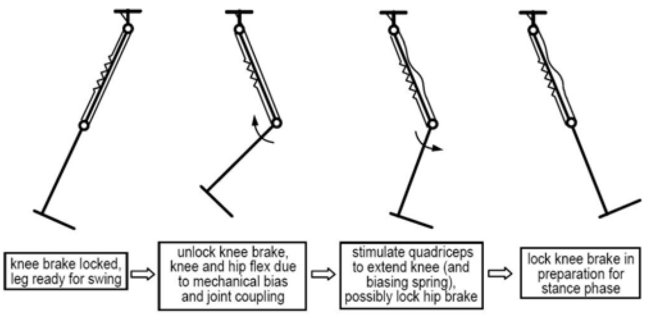

Fig. 3. Schematic representation of JCO swing phase of gait, indicating the cooperative behavior and sequencing of the knee and hip brakes, the mechanical bias spring, the unidirectional joint coupling, and the quadriceps stimulation.

C. Wafer Disc Brakes

A key component of the JCO is the wafer disc brake (WDB), which serves a threefold purpose: 1) provide added safety via the normally "locked" design of the knee brake, which will prevent the wearer from falling should the device lose power; 2) increase muscle efficiency by locking joints during phases of gait when they are normally static, thus taking the burden of support off the leg muscles, reducing muscle fatigue and allowing longer

(a) (b) (c) (d)

Fig. 4. (a) Femur link shown with joint biasing and coupling cable highlighted in red, (b) detail view of knee joint, showing joint biasing and coupling cable, (c) detail view of hip joint, showing joint coupling cable in the engaged position (e.g., during the knee flexion part of swing phase), and (d) detail view of hip joint, showing joint coupling cable in the disengaged position (e.g., during knee extension part of swing phase). Note that while in the disengaged position, the hip cable is guided around the inside of the hip joint housing, as shown in (d). Note that this figure is clearest when viewed in color.

walking times; and 3) smooth and control leg trajectories for a more natural and repeatable gait by utilizing the brakes as variable dampers controlled in relation to joint angle feedback. A previous effort to create a controlled brake orthosis [20, 24, 25] utilized magnetic particle brakes, which require electrical power to impose resistive torque. In the event of a power failure, the brakes (and thus the orthosis joints) remain unlocked, which could result in collapse and serious injury to the individual. The authors have developed a new type of brake, called a wafer disc brake, which provides nearly 45 times the torque-to-weight ratio of state-of-the-art magnetic particle brakes, and importantly, can be designed in either a “normally locked” mode or “normally unlocked” mode. Since the knee joints should fail in a locked mode, as previously mentioned, the knee brakes are thus of the normally locked type. Since the hip brakes are used primarily for trajectory control and are characterized by relatively low duty cycle operation, the hip brakes are of the normally unlocked type. Designing knee brakes to be normally locked and hip brakes to be normally unlocked both minimizes electrical power consumption (based on data from [25], and importantly prevents collapse during an electrical power failure. The normally unlocked WDB, which was designed for the hip joint, consists of a stack of thin high-strength plastic wafers which are alternatively coupled (through splines) to the brake stator and rotor. A small brushless motor located inside the brake shaft transmits a compressive force through a ball screw to the stack. Assuming relatively low friction in the ball screw, the stack is subjected to a compressive force which is proportional to the motor current. Due to the series arrangement of discs, the resistive torque on the rotor is the product of the compressive force, the mean radius of contact, and the coefficient of friction, which is amplified by the number of interfaces between discs. Since the hip brake contains 71 discs, the effective hip torque is increased by a gain of 70. Since the ball screw is back-drivable, the brake torque remains in proportion to the motor current, and thus is proportional in nature. The normally locked type of WDB, which is used for the knee joint, is shown in cross-section in Fig. 6. A photo of the corresponding assembled prototype is shown in Fig. 7. The design is similar to the normally unlocked type, but the discs are preloaded with a compression spring. Applying current to the motor proportionally unloads the preload, such that full brake torque occurs at zero motor current, and minimum brake torque occurs at full motor current. Since the ball screw is back-drivable, the brake torque remains in inverse proportion to the motor current.

A first-generation prototype of the knee brake has been constructed and tested. The mass of this brake is 0.73 kg. The brake was experimentally measured to provide a maximum torque of 50.7 N-m, which provides a resistive torque-to-weight ratio of 69.4 N-m/kg. In comparison, a state-of-the-art magnetic particle brake (MPB) in a similar size range provides a torque of 1.7 N-m with a mass of 1.14 kg, and as such has a resistive torque-to-weight ratio of 1.5 N-m/kg (e.g., Placid Industries model no. B15). As such, the WDB has a torque-to-weight ratio approximately 45 times greater than the MPB. Experimental measurements further indicate a minimum torque of 0.16 N-m (i.e., the brake dynamic range is between approximately 0.2 and 50 N-m). Note that this provides a dynamic range ratio of 250:1. The aforementioned MPB has a dynamic range of 100:1, and thus the WDB provides significantly improved performance (relative to the MPB) with respect to both torque/weight ration and dynamic range. For both WDB brake types, the torque varies linearly (and inversely, for the knee brake) with input current.

D. Ankle Support

The JCO utilizes an ankle-foot-orthosis (AFO) at the ankle, which is sufficiently compliant to allow

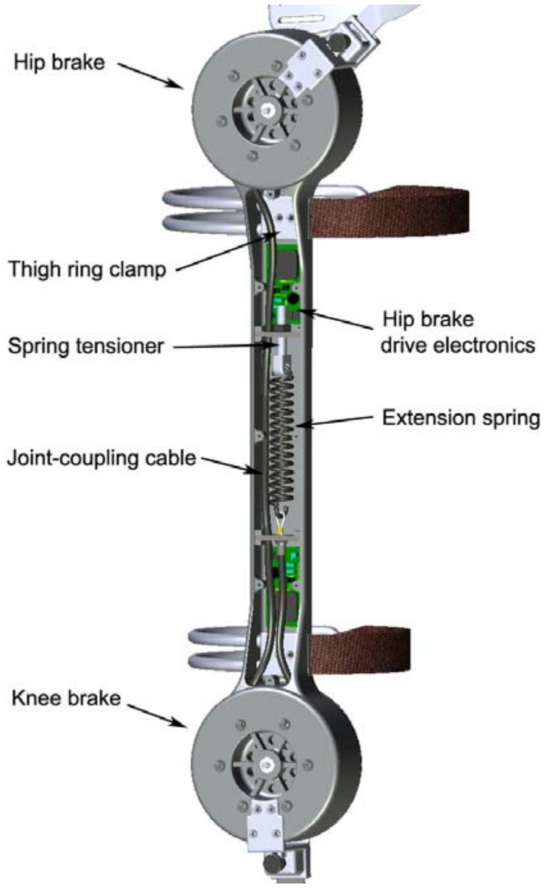

Fig. 5. Femur link detail.

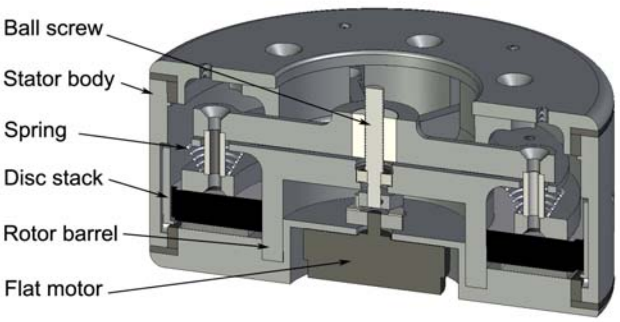

Fig. 6. Cross-section of normally locked knee brake.

dorsiflexion during the stance phase of gait, but sufficiently stiff to prevent foot drop during the swing phase of gait. Current gait simulations indicate a stiffness of 15 Nm/rad (for a 75 kg user) provides an appropriate balance between these objectives.

E. Mass and Inertia

The total orthosis mass as shown in Fig. 1, based on the solid model and prototypes of the brakes, is approximately 6 kg (13 lbs). Approximately one half of the orthosis weight is located on the pelvis, and thus does not add significantly to the rotational inertia or gravitational loads of the lower limbs. The rotational inertia of the distal link of the orthosis about the knee joint is approximately 5% of a typical shank inertia, while the inertia of the proximal link about the hip joint is about 10% of a typical thigh inertia.

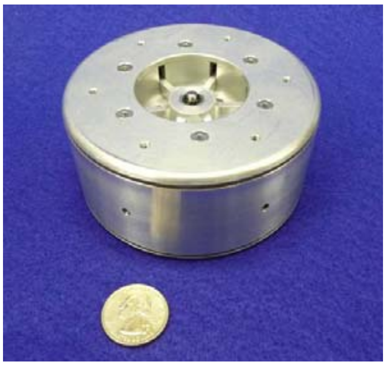

Fig. 7. Fully functional knee brake prototype.

F. Donning and Doffing

Along with reliability, function, and perceived and measurable benefit, one of the most important factors in the acceptance and use of a gait restoration system is ease of use, and chief among this factor is the ability of the user to quickly and easily don and doff the system. The JCO was designed to be donned (and doffed) quickly, easily, and independently, while sitting. The JCO consists of five component parts, which are separately donned and snapped together via structural quick connect joints. Specifically, the JCO is separated into two AFO's, two thigh segments, and a waist harness, shown in Fig. 8.

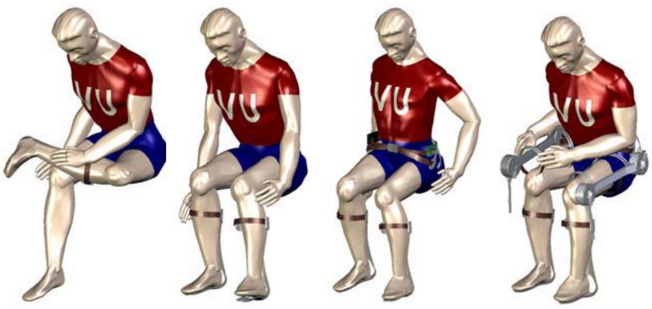

Fig. 8. Depiction of steps for donning JCO.

III. SIMULATION

A simulation of the JCO and gait controller was conducted for a user of height L=1.7m and mass M=65kg. Detailed simulation results are reported in a companion paper. The cadence of the resulting gait was 34 steps per minute and the average velocity was 0.2 m/s. A depiction of the simulation progression is shown in Fig. 9. Importantly, the simulation indicates a required quadriceps stimulation duty cycle of approximately 15%.

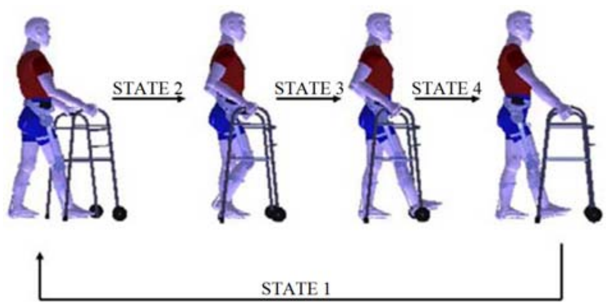

Fig. 9. Progression of simulation states.

IV. Preliminary Experiments

The authors have conducted preliminary experiments to test the joint coupling concept, and to assess the extent of fatigue imposed by the bias spring and joint coupling. A preliminary, one-legged version of the orthosis was created which included one-to-one joint coupling between the hip and knee, an adjustable extension spring for knee flexion, potentiometers on the hip and knee joints for angle measurement, and a locking knee joint with quick release pin. Experiments were conducted to 1) determine if the spring and joint coupling could provide sufficient knee and hip flexion in the context of stride, and 2) determine if the quadriceps could repeatably provide the power necessary to overcome the spring and extend the lower leg without significant fatigue. The first experiment (see Fig. 10) involved positioning an able-bodied subject in stance such that the leg wearing the orthosis was in the rear and ready to begin stride. The spring was loaded and the knee was locked in the extended position by means of a quick connect pin. As the pin was pulled, the leg swung forward in knee and hip flexion as shown in Figs. 10 and 11. At the peak of hip flexion, the quadriceps was stimulated, which fully extended the knee. Based on the resulting motion, the proposed approach appears to provide hip and knee swing motion necessary for gait restoration.

The second experiment involved conducting extended sets of pulsed quadriceps stimulation at a duty cycle of 15%— as indicated by the gait simulations. Ten subjects underwent three five minute periods of stimulation with a rest period in between each trial of three minutes.

Representative data (showing stimulation duty cycle and knee and hip angles) for a few cycles of stimulation for a single subject is shown in Fig. 12. Note that, since the test orthosis does not include a locking knee brake, the hip and knee joints return to the flexed position immediately following the quadriceps stimulation (unlike in the proposed gait sequence, in which the knee joint would be locked at full extension following quadriceps stimulation, and would unlock only during the swing phase of gait). Representative knee angle data for an entire five-minute trial is shown in Fig. 13.

For each subject, the amplitude of knee motion corresponding to each flexion/extension cycle was collected and plotted versus cycle (84 cycles per trial, 252 cycles total for the three trials). A representative plot of this data for a single subject is shown in Fig. 14, which also shows a least-squares-fit line through each of the three consecutive five-minute trials. Note that the discontinuity in the lines is due to the three-minute rest period between trials. The average decrease in flexion angular displacement (across all subjects) over the first five-minute trial was 13% and over the second five-minute trial was 10%. As shown in Fig. 14, however, the average flexion amplitude (across all subjects) during the third trial showed no decrease (in fact showed a 1% increase).

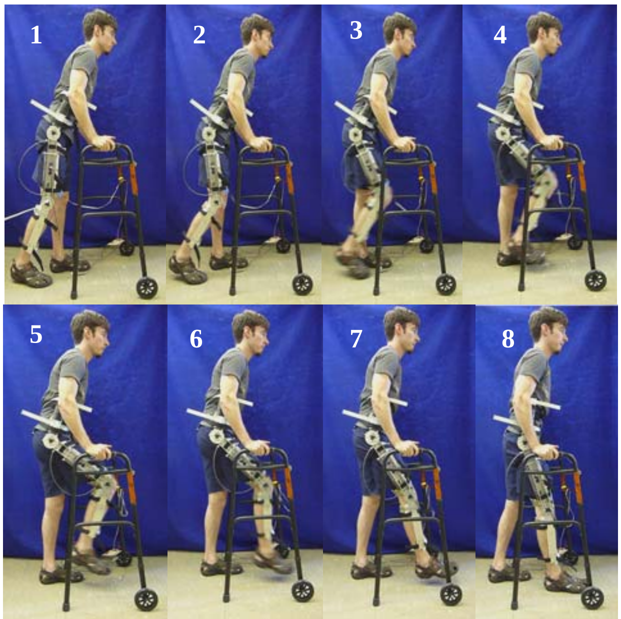

Fig. 10. FES/JCO generated gait sequence experiment. ***Frame 1:*** Right leg is locked in shown position. Assistant pulls pin to unlock the knee joint. ***Frames 2-5:*** Once pin is pulled, the spring pulls the knee into flexion and the joint coupling therefore pulls the hip into flexion as well. Frame 5 is the final resting state under no muscle contraction. ***Frames 6-8:*** The quadriceps is stimulated by a momentary push button switch on the walker handle. This causes the knee to extend and therefore relieve the joint coupling, allowing the hip to extend also. Frame 8 is the final resting position of the leg after it has rejoined the ground after stride.

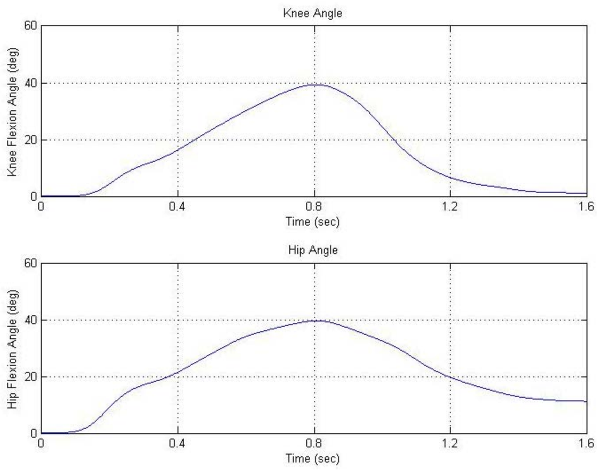

Fig. 11. Joint angle data during gait experiment shown in Fig. 12.

Thus, for conditions representative of the proposed approach, the data appears to indicate stabilization in average flexion amplitude by the third five-minute trial. More specifically, based on the averaged data of ten subjects, the flexion amplitude appears to have stabilized at approximately 85% of the mean amplitude exhibited during the first five-minute trial. Importantly, this apparent stabilization indicates that, for the 15% duty cycle and workload imposed on the quadriceps by the JCO, the proposed approach should be capable of providing long periods of locomotion unimpeded by quadriceps muscle fatigue.

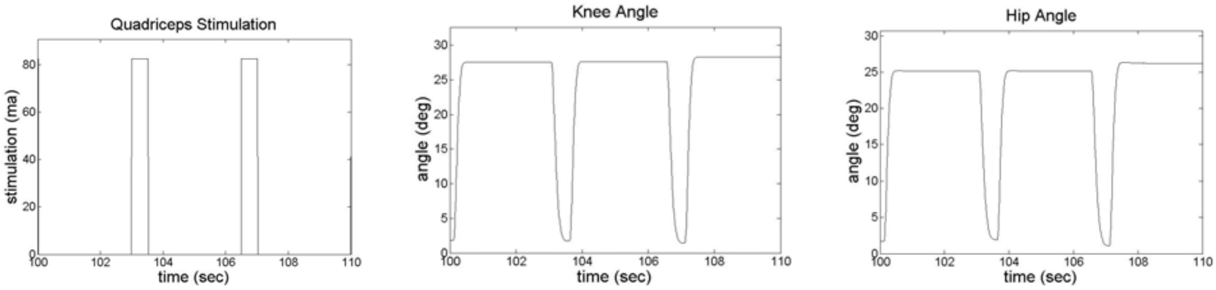

Fig. 12. Representative data from the quadriceps fatigue experiments, showing amplitude of quadriceps stimulation, knee angle as measured by the test orthosis, and hip angle.

V. Conclusion

A joint-coupled controlled brake orthosis (JCO) has been designed as part of a hybrid FES/orthosis system for restoring gait to spinal cord injured individuals. This device will 1) unidirectionally couple hip to knee flexion; 2) aid hip and knee flexion with a spring assist; and 3) incorporate sensors and modulated friction brakes, which are used in conjunction with electrical stimulation for the feedback control of joint (and therefore limb) trajectories. A one-legged joint coupling prototype was used to validate the joint coupling concept and assess the fatigue induced by the system upon the quadriceps muscles. Based on the motion obtained using the prototype and quadriceps stimulation, the proposed approach appears to provide hip and knee swing motion necessary for gait restoration. Furthermore, results from the preliminary fatigue testing showed that muscle output appeared to stabilize at 85% of the its initial output after 15 minutes of stimulation. As such, the quadriceps appears to be capable of providing sustained power for the proposed hybrid approach to support continuous walking without significant degradation of performance. Future work includes characterization of the latest brake prototype, development of a fully functional, two-legged JCO, control design, on-board electronics, and clinical trials of the JCO system.

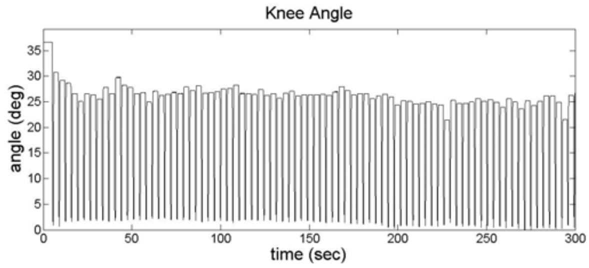

Fig. 13. Representative data from a five-minute trial for FES powered knee (and hip, via joint coupling) extension while wearing the test orthosis.

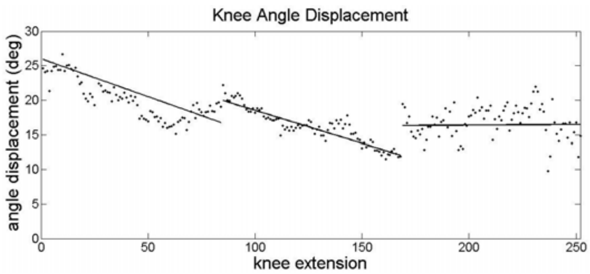

Fig. 14. Representative data from a single subject for three consecutive (five-minute) trials, and least-squares fit line for each trial. The discontinuity in lines is due to the three-minute rest between trials.

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