Preliminary Design of an Energy Storing Orthosis for Providing Gait to People with Spinal Cord Injury

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Abstract— **A new design is proposed for an energy storing orthosis (ESO) that restores walking to people with spinal cord injury by combining functional electrical stimulation of the quadriceps muscle with a mechanical brace that uses elastic elements to store and transfer energy between hip and knee joints. The new ESO is a variation of a previous design and uses constant force springs for energy storage. Based on the detailed design and on dynamic simulations, the concept has demonstrated preliminary technical feasibility.**

I. INTRODUCTION

Individuals with spinal cord injury (SCI) have limited modes of transportation. The wheelchair is the most common mobility aid, but 64% of SCI respondents prioritized walking as the main form of mobility to experience again [1]. Standing is another priority at 25%, and can provide health benefits compared to spending long periods in a wheelchair [2]. There are 273,000 people living with SCI injuries in the U.S. with approximately 12,000 new cases each year [3].

Several technologies that enable people with paraplegic SCI to stand or walk have been developed. They include functional electrical stimulation (FES), externally powered orthosis, and orthotic bracing. FES is the contraction of muscles by electrical stimulation to cause or drive limb movement. This technology has been shown to improve health and longevity of the user and the muscles [4-6]. Electrodes that cause stimulation are connected to the muscles by implantation directly into the muscle or on the surface of the skin. Implantation is done through surgical techniques and is usually left in the muscle permanently [7]. By stimulating multiple muscles systematically FES can produce assisted standing and gait [8,9]. There are limitations when using FES alone to achieve gait. Muscle fatigue can occur quickly when using FES [10]. Depending on which muscles are being stimulated, placement of the electrodes can be difficult to achieve optimal muscle output for both implanted and surface stimulation. Joint control can also be difficult using FES because of the high number of degrees of freedom and because muscle output is not repeatable with stimulation input.

Externally powered exoskeletons generate torque to drive the joints to achieve gait [11,12]. The power sources vary and examples include batteries and pneumatics. Electric motors are the most common way to drive the joint with rigid orthotic bracing on each leg. Since external power is needed, power sources must be incorporated into the device, which can lead to the device being heavy, and the user carrying large loads usually in the head-arm-torso (HAT) region. Also, external power sources can quickly run out of energy, which makes these devices impractical for everyday use.

Hybrid devices combine useful aspects of the different gait technologies [13-18]. One type of hybrid device combines FES with orthotic bracing for better joint control. Using this concept, muscle fatigue can be reduced by better joint control and by locking the joints and relaxing the stimulated muscle to conserve energy as the walking cycle advances. For example, Goldfarb et al. used magnetic particle brakes for joint control with FES [14]. The energy storing orthosis (ESO) is another type of hybrid device [13,15,17,18]. The ESO stored energy and used the energy with specific timing to drive gait. The advantage of this device is that no external power source is needed other than the power required for muscle stimulation. Further, with the ESO, stimulation of only one muscle can provide the energy that is stored in the device. This indicates that the ESO devices should be lighter than the externally powered gait devices. Another concept for an energy storage device was developed by Quintero et al. who completed the preliminary design of the joint coupled orthosis (JCO) using an energy storage concept [16].

In this paper the concept and preliminary design for a new ESO device is described. It is based on our previous ESO work [15,18], but uses constant force springs to store and transfer energy, rather than the pneumatic and elastomeric springs used previously. Our new ESO uses FES of the quadriceps to drive the knee and also to store energy to produce the gait sequence shown in Fig. 1. The quadriceps muscle is a suitable muscle for surface FES because of its large area and ease of electrode placement. Once the muscle energy is stored the joints are locked and unlocked with specific timing to prevent muscle fatigue. The purpose of the work described here was to determine if the new ESO design is feasible to enable continuing development. Here, we focus on the hip and knee joint mechanisms, which are novel, and not on the entire orthosis or body attachment points, which are conventional.

II. CONCEPT DESCRIPTION

The gait produced by the ESO has four phases as shown in Fig. 1. The required joint ranges of motion are taken from Goldfarb et al. [14]. The four phases are: equilibrium, stimulation, foot ground contact, and hip extension.

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The first phase of the gait cycle is the biased equilibrium position of the leg. To hold the leg in place at this position a locking mechanism is needed at both the hip and knee joints, or gravity would prevent the leg from staying at these angles. Springs at the hip and knee are needed to hold the leg in this position against gravity when the locking mechanism is unlocked.
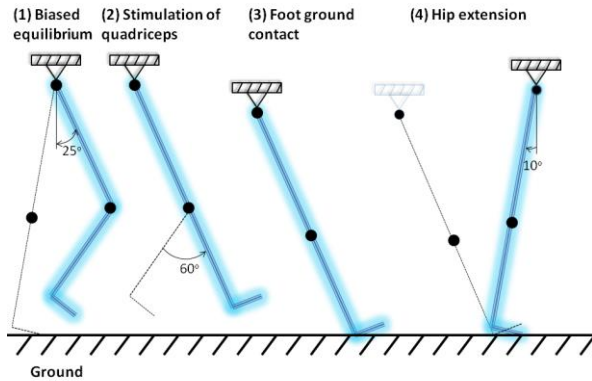

Figure 1.   Three phases of the ESO gait cycle.

To transition to the second phase, FES of the quadriceps is applied that results in the knee swinging to full extension as shown in Fig. 1. To prevent muscle fatigue the knee joint is locked at full extension and the FES switched off. During knee extension energy from the quadriceps is also being delivered to mechanical energy storage elements that in turn release their energy at later points in the gait cycle. After the knee is fully extended, the user falls forward onto the foot of this extended leg to the foot ground contact position.

The transition to the hip extension phase occurs through energy release from the storage element into the hip joint. Again the locking mechanism at the hip is important to conserve quadriceps energy from being released at improper times during gait. The final release of quadriceps energy takes place as the leg moves from phase 4 back to phase 1. Energy storing mechanisms will flex the leg back to the starting equilibrium position.

III.   DESIGN DESCRIPTION

A. Structure

The preliminary ESO design for the right leg only is shown in Fig. 2. The left leg of the design is a mirror image. Since we are currently interested in the technical feasibility of the concept, the rest of the orthosis above and below the thigh segment is not shown. Further, all of the important joint locking, energy storage and energy transfer components are located on the thigh segment of the ESO.

Constant force springs were chosen for the energy storing elements. There are three springs in the ESO, a hip equilibrium spring, a knee equilibrium spring and an energy transfer spring. The knee spring and the transfer spring store energy when the quadriceps is stimulated. The hip spring stores energy when the transfer spring is released.
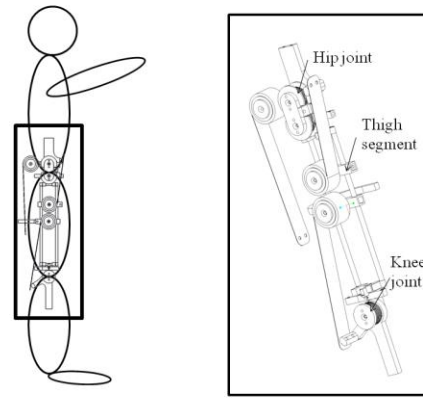

Figure 2.   Thigh segment for the ESO.

B. Design Specifications

Table 1 shows the design specifications for the ESO. Requirements 1 and 2 enable the user to sit in a wheelchair with the device. This is needed when resting, and also for donning and doffing the device. Requirement 3, locking torque, prevents the user from collapsing while wearing the device and was derived from earlier work [15]. Requirement 4, equilibrium torque, is what is needed to move the leg to the equilibrium position. These requirements were calculated using static analysis. Because the thigh segment contains no motors and no batteries, its weight should be less than competing devices, which drives Requirement 5. The listed weight goal is from our previous ESO [15].

TABLE I.   ESO DESIGN SPECIFICATIONS

No.	ESO Design Specifications		
	Metric	Unit	Value
1	Lateral width	m	<0.54
2	Seated join angle hip	Deg	105F
	Seated joint angle knee	Deg	90F
3	Locking torque: hip and knee	Nm	>31
4	Equilibrium torque hip	Nm	>7.5
	Equilibribrim torque knee	Nm	>8.2
5	Thigh segment weight	kg	<4.34

C. Hip Joint

The hip joint is shown in Fig. 3. Energy storing from the quadriceps takes place in a constant force spring made of AISI 301 stainless steel. The connection for the thigh equilibrium constant force spring is also located on the hip joint. The anchor points of the springs were carefully selected to provide the desired joint torques.

A custom wrap spring brake is used to lock the joint. Wrap spring brakes work by allowing rotation in one direction, but when locked, not the other. With the ESO gait sequence, during certain phases, the hip cannot rotate in either direction so two coupled wrap spring brakes are used. Shafts hold the two wrap springs, and 2024 aluminum alloy gears transfer the motion between the two brakes. Miniature

servo motors (Hitec, HS-35HD Ultra Nano) are used to unlock the wrap springs.
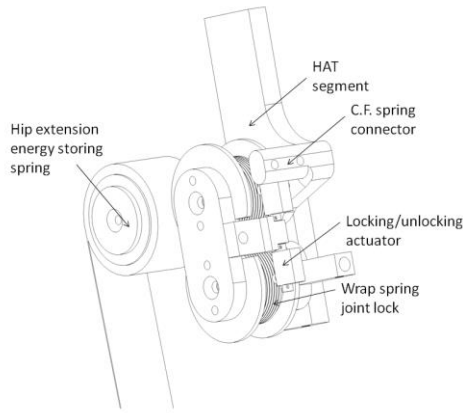

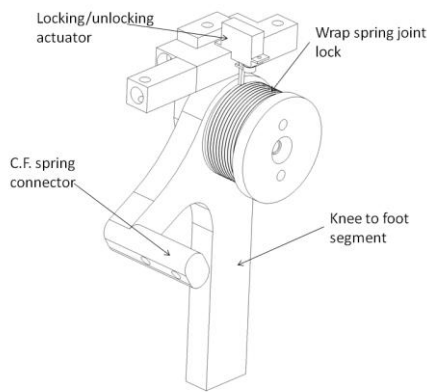Figure 3.   Hip joint design.

D. Knee Joint

Figure 4.   Knee joint design.

The knee joint is similar to the hip joint in materials, components and function, and is shown in Fig. 4. One difference is the need to lock knee rotation in only one direction, which means there is a single wrap spring brake at the knee. Extension rotation is always allowed because the stimulation can be turned off and the knee will no longer rotate in that direction due to energy stored in the knee equilibrium spring. The knee spring is connected to the knee joint at a desired radius arm distance to generate the needed torque for holding the joint in the equilibrium position.

E. Component Choices

Two components are critical for the operation of the ESO: the joint locks and the energy storage springs. For locking the joints, wrap spring brakes were chosen. Other options include friction brakes, serrated plates, or dog clutches. Wrap spring brakes are advantageous for several reasons. The first is user safety. If power failure of the device occurs the wrap spring unpowered position locks the joint, preventing collapse of the user. Another advantage is the fast response because the spring can be actuated with just a small

motion of the spring's control tang. A third advantage, which is unique to wrap springs, is that the brake can be unlocked under load with only a small force needed to move the spring tang. This means that a small brake actuation mechanism can be used saving space and weight. A fourth advantage is that the wrap spring brake has an exceptional holding torque to weight ratio and a relatively small device can be used to hold the torques seen at the ESO joints when fully loaded.

Constant force springs were chosen for the energy storage component. Other options include coil springs, gas springs and rubber bands. Constant force springs have a constant force output while being actuated, unlike coil springs whose force is proportional to deflection. This is an advantage because the largest torque that is needed is when the joints are in the flexed position and for a coil spring; this is where its force is lowest. Further, with a coil spring, as the knee extends, more and more stimulated quadriceps force would be needed to extend the spring which could result in overexertion and rapid fatigue of the muscle. Constant force springs maintain the same force lowering the overall work required by the quadriceps to reach full extension.

IV. EVALUATION

The CAD model was used to verify the size and weight requirements for the ESO. The overall width of the design is 0.505 m while still accommodating the hip width of the average adult male. This is below the specification for allowing the user of the device to fit into a wheelchair when sitting down. The ESO device's mass, based on appropriate component densities entered into the CAD model, is about 2.5 kg, which is under the requirement. Further, while not a requirement, the joint is compact, extending only 0.032 m above the hip and 0.025 m below the knee.
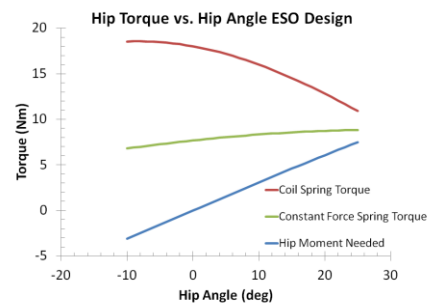

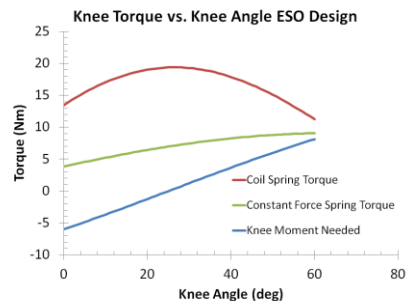Figure 5.   Hip torque profiles.

Figure 6.   Knee torque profiles.

The torques each joint experience due to gravity along with the energy storing components was estimated using a static analysis. Leg parameters, such as weight, size, and center of gravity, of an average male were used for the static calculations [19]. By specifying a range of joint angles, the needed torque to hold the leg at the angles could be calculated. Fig. 5 and Fig. 6 show the torque of the hip and knee joints as functions of the joint angles. Torque profiles are displayed for both a coil compression spring and constant force spring that are capable of meeting the needed torque to lift the leg to the biased equilibrium position. Compression springs do not follow the needed torque curve as well as the constant force spring showing that energy from the quadriceps will be wasted to overcome this additional torque.

The joint locking torque was modeled to hold the user in the standing position without collapse. Static analysis showed that a locking torque greater than 31 Nm is needed [15]. The wrap springs that are used for this design have a locking torque of 40 Nm, with the wrap spring torque calculations based on the work of Irby et al. [20].

V. Dynamic Simulation Model

A dynamic simulation model implemented in Matlab and SimMechanics was used to evaluate the timing and verify the operation of the concept. The leg of an average male plus the ESO structure were modeled as one two link mechanism with the appropriate weights and center of gravity [19]. External forces, torques and spring components were attached to these linkages to model the stimulation of the quadriceps and the energy storage components.

The simulation predicted a step cycle time of 2.7 s when the simulated knee torque caused by FES of the quadriceps was set to 15 Nm. While considerably slower than the step cycle time of 1 s for non-impaired walking, it is in the range of other FES walking devices [14]. The cycle time could be reduced with higher values of quadriceps force.

VI. Conclusion

The ESO described in this paper is a new hybrid orthosis concept for restoring walking to people with spinal cord injury. The main components of the design are the energy storing and joint locking components. Initial evaluation of the main components of the ESO design reveals that the concept should be feasible for accomplishing gait. To validate the design, a working prototype and testing on users is needed.

References

[1] D. L. Brown-Triolo, M. J. Roach, K. Nelson, and R. J. Triolo, "Consumer perspectives on mobility: implications for neuroprosthesis design," *J Rehabil Res Dev*, vol. 39, no. 6, pp. 659–669, Nov. 2002.

[2] P. W. Axelson, D. Gurski, and A Lasko-Harvill, "Standing and its importance in spinal cord injury management," in *Proc. RESNA 10th Annu. Conf.*, 1987, pp. 477-479.

[3] NSCISC, *2012 Annual Report: Spinal Cord Injury Model Systems*. Birmingham, Alabama, 2012.

[4] P. J. Pacy, R. H. Evans, and D. Halliday, "Effect of anaerobic and aerobic exercise promoted by computer regulated functional electrical stimulation (FES) on muscle size, strength and histology in paraplegic males," *Prosthet Orthot Int*, vol. 11, no. 2, pp. 75–79, Aug. 1987.

[5] D. Guiraud, C. Azevedo Coste, M. Benoussaad, and C. Fattal, "Implanted functional electrical stimulation: case report of a paraplegic patient with complete SCI after 9 years," *J Neuroeng Rehabil*, vol. 11, no. 1, p. 15, Feb. 2014.

[6] G. A. Wu, L. Lombardo, R. J. Triolo, and K. M. Bogie, "The effects of combined trunk and gluteal neuromuscular electrical stimulation on posture and tissue health in spinal cord injury," *PM R*, vol. 5, no. 8, pp. 688–696, Aug. 2013.

[7] J. A. Davis Jr, R. J. Triolo, J. P. Uhlir, N. Bhadra, D. A. Lissy, S. Nandurkar, and E. B. Marsolais, "Surgical technique for installing an eight-channel neuroprosthesis for standing," *Clin. Orthop. Relat. Res.*, no. 385, pp. 237–252, Apr. 2001.

[8] E. Marsolais and R. Kobetic, "Functional electrical stimulation for walking in paraplegia," *J Bone Joint Surg Am*, vol. 69, no. 5, pp. 728–733, Jun. 1987.

[9] R. Kobetic, R. J. Triolo, and E. B. Marsolais, "Muscle selection and walking performance of multichannel FES systems for ambulation in paraplegia," *IEEE Transactions on Rehabilitation Engineering*, vol. 5, no. 1, pp. 23–29, Mar. 1997.

[10] J. M. Hausdorff and W. K. Durfee, "Open-loop position control of the knee joint using electrical stimulation of the quadriceps and hamstrings," *Med Biol Eng Comput*, vol. 29, no. 3, pp. 269–280, May 1991.

[11] H. A. Quintero, R. J. Farris, C. Hartigan, I. Clesson, and M. Goldfarb, "A Powered Lower Limb Orthosis for Providing Legged Mobility in Paraplegic Individuals," *Top Spinal Cord Inj Rehabil*, vol. 17, no. 1, pp. 25–33, 2011.

[12] A. Esquenazi, M. Talaty, A. Packel, and M. Saulino, "The ReWalk powered exoskeleton to restore ambulatory function to individuals with thoracic-level motor-complete spinal cord injury," *Am J Phys Med Rehabil*, vol. 91, no. 11, pp. 911–921, Nov. 2012.

[13] W. K. Durfee and A. Rivard, "Design and simulation of a pneumatic, stored-energy, hybrid orthosis for gait restoration," *J Biomech Eng*, vol. 127, no. 6, pp. 1014–1019, Nov. 2005.

[14] M. Goldfarb and W. K. Durfee, "Design of a controlled-brake orthosis for FES-aided gait," *IEEE Trans Rehabil Eng*, vol. 4, no. 1, pp. 13–24, Mar. 1996.

[15] A. Kangude, B. Burgstahler, and W. Durfee, "Engineering evaluation of the energy-storing orthosis FES gait system," *Conf Proc IEEE Eng Med Biol Soc*, vol. 2010, pp. 5927–5930, 2010.

[16] H. A. Quintero, R. J. Farris, M. Goldfarb, and W. K. Durfee, "Feasibility of a Hybrid-FES System for Gait Restoration in Paraplegics," *Conf Proc IEEE Eng Med Biol Soc*, vol. 2010, pp. 483–486, 2010.

[17] W. K. Durfee and A. Rivard, "Preliminary Design and Simulation of a Pneumatic, Stored-Energy, Hybrid Orthosis for Gait Restoration," pp. 235–241, Jan. 2004.

[18] A. Kangude, B. Burgstahler, J. Kakastys, and W. Durfee, "Single channel hybrid FES gait system using an energy storing orthosis: preliminary design," *Conf Proc IEEE Eng Med Biol Soc*, vol. 2009, pp. 6798–6801, 2009.

[19] R. Drillis, R. Contini, and M. Bluestein, "Body Segment Parameters; a Survey of Measurement Techniques," *Artif Limbs*, vol. 25, pp. 44–66, 1964.

[20] S. E. Irby, K. R. Kaufman, R. W. Wirta, and D. H. Sutherland, "Optimization and application of a wrap-spring clutch to a dynamic knee-ankle-foot orthosis," *IEEE Trans Rehabil Eng*, vol. 7, no. 2, pp. 130–134, Jun. 1999.