THE USE OF ELASTIC ELEMENT IN A HYBRID ORTHOSIS FOR SWING PHASE GENERATION IN ORTHOTIC GAIT

S.Gharooni, M. O.Tokhi, B.Heller*
Department of Automatic Control and Systems Engineering
*Department of Medical Physics and Clinical Engineering, University of Sheffield
Email: c.s.gharoni@sheffield.ac.uk

Abstract: *A new technique for generating the swing phase in a passive orthosis is introduced in this paper. A spring is used for knee flexion. The gravity and inertial forces assist hip flexion and artificially stimulated muscle is used as the power source. This spring knee orthosis provides more-natural swing phase trajectory than that produced by the flexion reflex for gait in spinal cord injured subjects. To circumvent the complexity involved in accurately modelling stimulated muscle, a fuzzy logic controller (FLC) was adopted for prediction and for the control scheme. It is shown that hip flexion can be produced without the need for the withdrawal reflex, hip flexor stimulus or any mechanical actuator at the hip. A hip flexion angle of 21 degrees was achieved with a non-impaired subject wearing a prototype orthosis.*

Key words: FES, Paraplegic Gait, and Orthosis.

1. Introduction

Combinations of mechanical orthoses and muscle stimulation are called hybrid orthoses. Two major difficulties, which limit the effectiveness of conventional hybrid orthoses, for the production of gait are:

- Generating hip and knee flexion whilst avoiding muscle fatigue resulting from prolonged electrical stimulation.
- Generating foot ground clearance with minimal upper body effort.

Controlled-brake orthosis (CBO) concept was designed to address these limitations by utilising FES in combination with a long-leg brace that contains controllable brakes at both knees and hips. The system achieves desirable limb trajectories by utilising the stimulated muscles and withdrawal reflex as a source of unregulated power and regulating the power at each joint by control of the brakes. The system also reduces the effect of muscle fatigue by locking the controllable brakes to provide the isometric joint torque necessary during stance [1]. However, disadvantages of the CBO (and any orthoses, which use the withdrawal reflex) are habituation, delayed response of the muscle contraction and the complicated control of joint trajectory.

2. Spring Brake Orthosis

In this study it is proposed that active contraction of muscles that flexes the leg might be artificially replaced by a spring knee orthosis to provide a more-natural swing phase trajectory than that produced by the flexion reflex for gait in spinal cord injured subjects. The spring brake orthosis (SBO) is a new gait restoration system in which stored spring elastic energy and potential energy of limb segments are utilised to aid gait as shown in Fig.1.

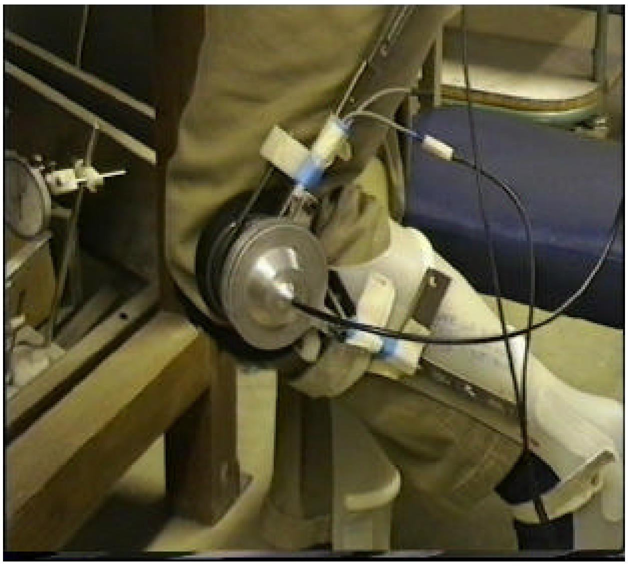

Fig. 1. Prototype SBO orthosis

This energy is released as kinetic energy at the optimal time to provide the desired limb motion. A hybrid SBO approach is proposed in which a mechanical orthosis with on-off brakes at the hip and knee, and a spring to oppose knee extension are combined with electrical stimulation of the knee extensors. A low duty cycle of quadriceps stimulation is assumed to lead to low muscle fatigue. It is also shown that hip flexion can be produced without the need for withdrawal reflex, hip flexor stimulus or any mechanical actuator at the hip. Also simultaneous hip and knee flexion leads to improved ground clearance compared to conventional fixed knee reciprocating gait orthoses.

3. Swing Phase Modelling

The swing phase model was assumed to be a double pendulum with an external elastic element on the knee and viscous damping of joints. Minimal duration of stimulated bursts of the quadriceps is used as a source of power.

As has been discussed above, the production of hip flexion using FES via surface electrodes is difficult. However, if the knee is flexed by the correct spring torque the action of the accelerating shank will cause the hip to flex; additionally, the new orientation of the knee will cause the leg to adopt a new minimum energy configuration with a flexed hip. This latter point is illustrated in Fig. 2.

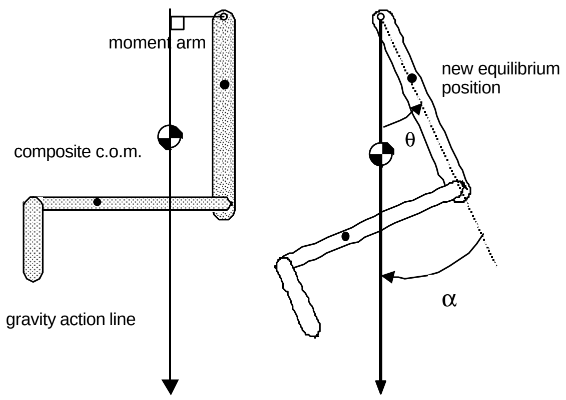

Fig. 2. Hip flexion resulting from flexed knee.

The static relationship between the knee angle (α) and hip angle (θ) is

$$tanq = sina/(2.426+cosa) \qquad (1)$$

The anthropometric data used in calculations is taken from Winter [2].

The amount of hip flexion produced by the dynamic inter segment coupling is dependent on the angular acceleration of the knee. Swing phase is initiated by releasing the brake at the knee joint to apply the spring moment to the orthosis joint. This causes knee flexes and consequent shank acceleration.

At the mid-swing phase the quadriceps muscle is simulated at a fixed stimulation level by the controller to return the shank to extension. Minimal duration of the stimulation bursts is assumed to yield minimal muscle fatigue.

A mathematical model of the swing leg was developed and the dynamic relationship between knee and hip movement was simulated and plotted in Fig.5.

It can be seen that the dynamic simulation produces a larger hip flexion than the static analysis. This is as expected because the inter-segment action on the thigh caused by the accelerating shank acts to flex the hip.

4. Fuzzy Logic Controller for FES-Drive of SBO

The complexity of the interface between the orthosis and stimulated limb can make the design of a system Controller even more complicated. A model–free FLC is employed in the FES-drive control scheme, thereby avoiding exact modelling of the complicated musculoskeletal-orthosis system as depicted in Fig. 3.

Fuzzy logic is a new way of translating the control strategies of a human operator to a control action. Fuzzy logic was introduced by Zadeh in 1965 to describe complicated systems which are difficult to analyse by traditional mathematics [3]. This method has gained popularity since its inception, and has proved to be an effective method in control engineering. The main advantage of the FLC approach is the possibility of implementing rules of thumb, experience, intuition, prediction and heuristics without the need for a mathematical model [4].

Generally, the control of a FES-drive can be achieved by adjusting some parameters of the stimulation patterns, i.e., the stimulation frequency, pulse width and the stimulation intensities.

The ideal approach is to minimum muscle fatigue and impact force in extreme knee extension. The conventional closed loop feedback controller stimulates knee extensors through out the trajectory. This may cause prolonged knee extensor stimulus in the mid-swing phase period and possibly some impact force on the knee at the end of extension.

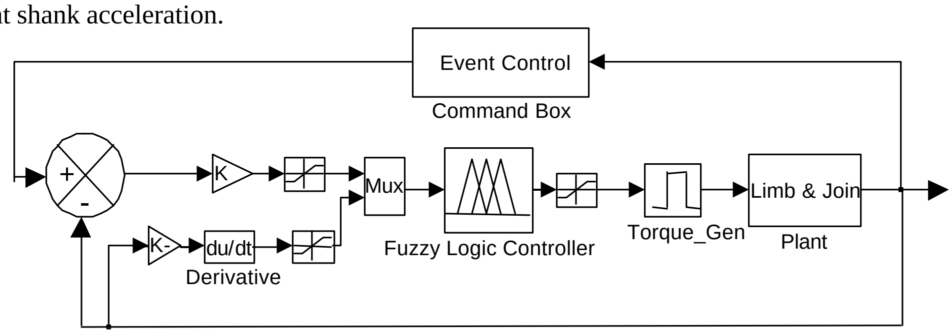

Fig. 3. The basic fuzzy logic controller for SBO

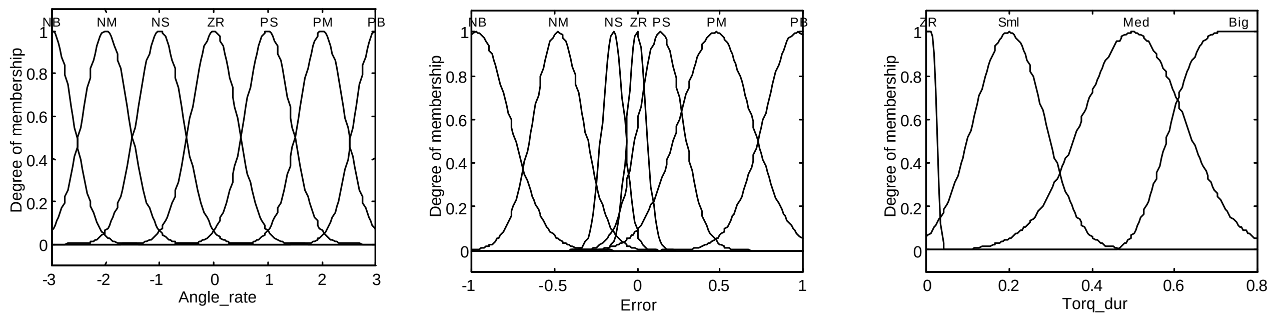

Fig. 4. Membership function for error, angular velocity and torque duration

The new stimulation proposes to stimulating quadriceps at maximal intensity which is safe and can be tolerated by the subject to accelerate the shank so much that it reaches full extension without any terminate impact force. This can be achieved by employing the FLC to determine the muscle torque duration required for full extension. Our simplified approach entails fixed stimulation patterns, that is, fixed stimulation pulse width and maximal amplitude. The stimulation begins just after the peak of knee flexion and its duration is determined by the FLC based on rules so that error and angular velocity (Figure 4) are considered as inputs to the controller and stimulator burst duration as an output.

The system has some tolerance to cope with changes in muscloskeletal parameters such as fatigue, nonlineararity and voluntary or involuntary movements in the body as these factors affect the error and angular velocity. Computer simulations of the SBO swing phase are plotted in Fig. 5.

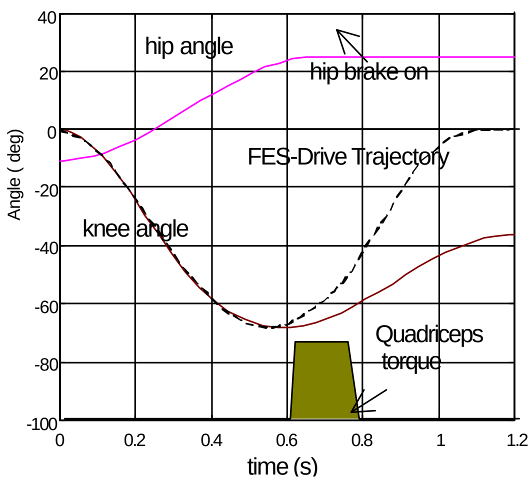

Fig. 5. Computer simulation of SBO swing phase

5. Normal Subject Results

A typical response of the hip and knee joints to sudden application of the spring moment and also quadriceps muscle stimulus at the optimal time is shown in Fig. 6. The brake was applied at the hip in maximum flexion. There was significant hip flexion (21 degree) corresponding with knee flexion (90 degree).

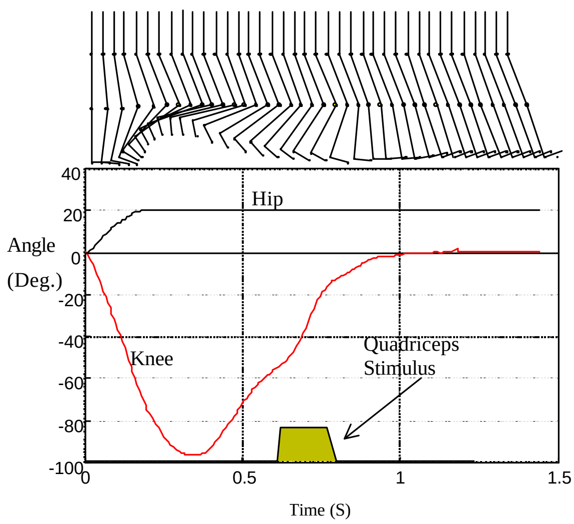

Fig. 6. SBO response to spring and muscle torque at the knee.

6. Discussion

The objective of the spring knee orthosis approach is to eliminate reliance on the withdrawal reflex with its problems of habituation and poor controllability. Instead, a simple switched brake with an elastic element such as a spring with well-defined properties would provide the necessary function and trajectory as shown in Fig. 6. As noted the technique is promising in producing functional hip flexion.

The merits of this technique include all the advantages of the controlled-brake orthosis (CBO) [5] with some additional advantages unique to the spring knee orthosis. Firstly, the SBO has the benefits of a powered orthosis, but the spring is used as a power actuator and the quadriceps muscle as the energy source (electrically stimulated muscle is a complex time varying actuator but a spring is a mechanical element with well defined properties). Therefore, there is no need for the heavy and bulky battery and DC motor to be carried as in the powered orthosis [6-7]. Also, unlike the DC motor actuator, the spring-mass response is similar to muscle-mass response and the spring is a passive device with no active failure modes which could cause damage by overriding the limb. Secondly, unlike a CBO which dissipates extra power at the joint produced by stimulated muscle, the spring drives and determines the joint trajectory so eliminating any need for a damping element and minimising muscle power to prevent premature fatigue in the stimulated muscles. A disadvantage of the CBO and any orthosis which uses a mechanical damping element is excess power dissipation where as in the SBO nearly all of the work done by the muscle is stored in the spring, therefore little power is dissipated. Thirdly, this system is nearly conservative in level walking because of the nature of the spring-mass system. In knee flexion energy transfer from the spring to the limb segment works against gravity and converts elastic energy in spring to kinetic and potential energy. This potential energy of the limb segment is returned back to the spring during extension of knee. The natural frequency of the spring-mass system determines the swing time. The role of the quadriceps is to compensate for the small amount of energy lost by the orthosis joint damping and the viscous properties of the joint tissue. Fourthly, the task of the brake in the SBO is much simpler than the brake in the CBO since it just releases the joint at the beginning of the swing phase and locks in full knee extension in the stance phase. Therefore, there is no need for proportional control and it is possible to replace the brake with a mechanical latch with a simple on and off function. This latch can be locked during quiet standing and during occasional rest periods during gait without muscle stimulation. Finally, using only quadriceps stimulation in small bursts after mid-swing, knee extension, knee flexion and hip flexion can be produced without relying on the withdrawal reflex.

7. Conclusions

A hybrid spring knee orthosis for use in FES aided paraplegic gait was investigated. A simple mathematical model and prototype mechanical model were used to evaluate performance in controlling the free swinging leg. The results show.

1. The hybrid SBO offers a more natural leg swing with a simple on-off brake and a spring for knee flexion instead of relying on the withdrawal reflex.
2. The foot ground clearance is positive during the entire forward swing phase.
3. There is no muscle activity during stance as the brake maintains the leg in extension.
4. This approach should reduce upper-limb energy cost and stimulated muscle fatigue during swing because it eliminates the need to laterally lift the body for foot ground clearance and uses a minimal duration and number of stimulation pulses during the swing phase.

8. Acknowledgements

The authors would like to acknowledge the assistance given by the following
Medical Workshop, Royal Hallamshire Hospital, Sheffield
Iranian Research Organisation for Science and Technology (IROST)
Hugh Steeper Ltd, UK

References

[1] W. K. Durfee and J. M. Hausdorff, “Regulating knee joint position by combining electrical stimulation with a controllable friction brake,” *Annals of Biomedical Engineering*, vol. 18, pp. 575-596, 1990.

[2] D.A.Winter, “Biomechanics of Human Movement,” *Wiley and Sons, New York*, 1979.

[3] L. A. Zadeh, “Fuzzy Sets,” *Inform. Contr.*, vol. 8, pp. 28-44, 1965.

[4] A.Prochazka, “Comparison of natural and artificial control of movement,” *IEEE Trans. Rehab. Eng.*, vol.1, pp. 7-17, 1993.

[5] M. Goldfarb and W. K. Durfee, “Design of a controlled-brake orthosis for FES-aided gait,” *IEEE Transactions on Rehabilitation Engineering*, vol. 4, pp. 13-24, 1996.

[6] D. Popovic, L. Schwinlich, “Hybrid powered orthoses,” *Advances in external control of human ex-tremities IX*, pp. 95-104, 1987.

[7] J. Edwards and S. V. S. Rithalia, “Powered hip orthosis,” in *Neuroprothetics*, A. Pedotti, M. Ferrarin, J. Quintern, and R. Riener, Eds. Springer, 1996, pp. 483-492.