INTRODUCTION

Functional neuromuscular stimulation (FNS) can be utilized to restore walking function after spinal cord injury (SCI). While excellent at propelling the body forward, the high stimulation duty cycles and limited number of stimulation channels compared to lower extremity degrees of freedom result in unnatural gait patterns and rapid muscle fatigue. Combining a FNS system with a controllable lower extremity orthosis can alleviate these problems by reducing the degrees of freedom during gait. Typically, such hybrid neuroprostheses (HNP) lock the knee during stance phase to support body weight and reduce stimulation; however, these systems retain the stiff-legged stance phase typical of FNS walking systems.

We have developed a novel orthosis capable of regulating knee rotation by providing variable amounts of resistance through the use of MR fluid [1]. A finite state control system has been developed to utilize this mechanism in a HNP to restore and regulate stance phase knee flexion during FNS-driven gait. Such a system has the capability to restore functions which are unattainable with FNS walking systems, including controlled flexion for impact absorbance and forward stair descent.

METHODS

The advantages of allowing stance phase knee flexion have been previously reported in prosthetics [2]. We seek to effectively restore stance phase knee flexion through the use of a controllable orthosis in combination with FNS walking system. The FNS system will propel the body forward using contractions of the user’s muscles, while the orthosis will control the motion of the knee during stance phase. The controller functions based on feedback from sensors mounted on the lower extremity brace to monitor sagittal plane hip and knee angle and velocity, foot-ground contact at the heel and forefoot, and axial acceleration of the lower leg. A typical gait cycle can be split into six distinct phases: loading response, mid-stance, terminal stance, pre-swing, early swing, and late swing [3]. The distinct knee behavior during these six phases of gait suggests that a finite state machine can be implemented for use as a knee controller (Figure 1). A similar approach has been taken in the development of controllers for prosthetic knees [4].

Figure 1: Schematic representation of finite state controller for stance phase knee flexion control using a variable impedance orthosis. Conditions for moving between states are indicated along transition lines; colors indicate which sensor will monitor the control variable.

To minimize parasitic losses of limb motion under FNS activity, the VIKM will remain off during both swing phases, enabling them to be lumped into a single state. Transition between the five states will proceed as follows. State 1 begins when the ipsilateral foot contacts the floor; the damper is
turned on to absorb the shock of impact and accept the body weight. As forward progression continues, the damper regulates knee flexion caused by thigh inertia and body weight load at the proximal end of the femur. Once initial knee flexion passes a predetermined threshold (approximately 15° [3]), the controller transitions to state 2. Knee and hip extensors are turned on while the damper is turned off to facilitate transfer of the body weight vector to the anterior side of the knee joint. When the knee reaches near full extension (within 3°) the FNS is turned off and the damper is turned on to prevent flexion and to rest the muscles as the controller moves to state 3. When the contralateral foot contact is sensed, the transition to state 4 takes place; the damper is active, regulating knee flexion which occurs as the ipsilateral hip flexes under FNS control and the load of weight bearing is transferred to the contralateral side. Once the ipsilateral foot leaves the ground, the damper is turned off to allow unencumbered knee motion during swing, after which the cycle repeats.

The knee damper actively regulates stance flexion during states 1, 3, 4. During these states, a secondary controller is activated which monitors knee angular velocity and adjusts damping proportionally. The level of resistance supplied by the MR damper is controlled by the duty cycle of a high frequency (800 Hz) pulse width modulated signal attached to a MOSFET switch gait. An onboard microcontroller adjusts the values of digital outputs – three for each knee – based on the output from the proportional controller; this enables the damper to have eight distinct damping states with eight different duty cycles ranging from 0% to 90%. At 0%, the damper is off and provides minimal resistance to knee rotation (less than 4 Nm), while at 90% the orthosis provides up to 64.5 Nm of resistance [1]. At any time during stance, if the knee angle flexion velocity or knee angle exceeds a preset threshold, the damper duty cycle is set to 90% to prevent collapse until FNS stimulation can resume to extend the leg.

The controller was validated during level ground walking experiments with able body subjects. Real time assessment of gait phase was performed by the controller based on inputs measured from the sensor set described above. The results from the controller were verified by comparing with data collected using a Vicon® MX40 motion capture system (Vicon Motion Systems, Oxford, UK).

RESULTS AND DISCUSSION

During able body walking, the controller was able to successfully identify all phases of gait. Over an average of 22 strides, the damper was actively regulating stance phase knee flexion during initial impact/weight acceptance, terminal stance, and pre-swing while turning off to allow stance phase extension during mid-swing (Figure 2). The range of knee angle was slightly diminished compared to normal walking, which is likely due to passive resistance within the orthosis.

CONCLUSION

The data presented here indicate the finite state controller is able to appropriately actuate the variable impedance knee mechanism for control of stance phase knee flexion. Stance phase knee flexion is currently non-existent in FNS-only walking systems, and may provide opportunity for increased gait efficiency and expansion of walking functions to include other maneuvers which require controlled knee flexion, such as ramp and stair descent.

REFERENCES