A Semi-Active Hybrid Neuroprosthesis for Restoring Lower Limb Function in Paraplegics

Nicholas Kirsch, Naji Alibeji, Lee Fisher, Chris Gregory, and Nitin Sharma

Abstract— **Through the application of functional electrical stimulation (FES) individuals with paraplegia can regain lost walking function. However, due to the rapid onset of muscle fatigue, the walking duration obtained with an FES-based neuroprosthesis is often relatively short. The rapid muscle fatigue can be compensated for by using a hybrid system that uses both FES and an active orthosis. In this paper, we demonstrate the initial testing of a semi-active hybrid walking neuroprosthesis. The semi-active hybrid orthosis (SEAHO) supports a user during the stance phase and standing while the electric motors attached to the hip section of the orthosis are used to generate hip flexion/extension. FES in SEAHO is mainly used to actuate knee flexion/extension and plantar flexion of the foot. SEAHO is controlled by a finite state machine that uses a recently developed nonlinear controller for position tracking control of the hip motors and cues from the hip angle to actuate FES and other components.**

INTRODUCTION

Each year in the United States approximately 12,000 people suffer from a spinal cord injury (SCI), primarily as a result of vehicular incidents or falls [1]. 21.6% of the individuals that suffer a spinal cord injury are diagnosed with complete paraplegia, which takes away their ability to walk. This immensely limits their ability to perform normal activities of daily life. By sequentially applying functional electrical stimulation (FES) to the muscles of the lower limbs the gait motion can be restored. FES uses a low-level electrical current to stimulate the nerves that innervate the muscles to produce desired limb function. FES has also been shown to provide therapeutic benefits for the user, such as increased muscle mass and bone density [2], [3]. However, transcutaneous FES can cause rapid muscle fatigue and certain movements such as hip flexion can be difficult to stimulate and control, as hip flexors are inaccessible via surface electrodes. Because of these issues, FES-based walking restoration systems have achieved limited acceptability among persons with mobility disorders.

To overcome muscle fatigue, an orthosis can be combined with FES [4]–[7]. The addition of an orthosis lowers the metabolic cost of walking by providing rigidity and support, thus reducing the amount of force required by the user to support themselves with a walker. This also reduces the amount of stimulation required since standing can be supported by the orthosis while walking. However, hybrid orthoses that combine passive bracing with FES lack the ability to provide additional power during standing and stepping. As a result, they are not well-suited to compensate for muscle fatigue, which leads to a reduction in joint torques and significant limitations on the achievable duration of walking. Recently, powered orthotic devices, such as the Vanderbilt exoskeleton [8], ReWalk exoskeleton [9], Mina exoskeleton [10], and Ekso Bionics exoskeleton [11] have been developed to enable paraplegics to walk again. However, as the ability to sustain walking for a longer time period depends on the power source's capacity, an electric motor-based powered exoskeleton will need to house a larger, heavier battery. By combining FES with a powered orthosis [4], [12]–[17] some of the joint torques required to create the walking motion can be generated through FES. This would decrease the torque requirements of the motor, which means that smaller actuators could be used and that the motor's power requirement would be reduced. Combining FES with powered orthosis would lead to longer walking durations and lighter devices, and would have the aforementioned FES health benefits for the user.

In this paper, we discuss the development and control of a semi-active hybrid orthosis (SEAHO) using a finite state machine (FSM). SEAHO uses transcutaneous FES to actuate knee flexion/extension and plantar flexion, while hip flexion/extension is actuated using electric motors. Wrap spring clutches, which only prevent flexion when locked but are free in the direction of knee extension, have been added to the knee joints so that stimulation is not required during standing. The wrap spring clutches also help to keep the stance leg extended during a step. This paper will discuss the individual components of SEAHO, the control system that is being used, and present results from initial testing of the device on an able bodied subject.

SEAHO AND ITS CONTROL SYSTEM

SEAHO, shown in Fig. 1, can be broken down into three primary components: electric motors, FES, and wrap spring clutches. The electric motors (Harmonic Drive LLC, MA, USA), which are located at the hip joints, can generate a maximum torque of 40 Nm. Electric motors are used at the hip joints because it is difficult to use FES to stimulate hip flexors, as these muscle are not easily accessible using surface electrodes. While it is possible to generate reflexive hip flexion via peroneal nerve stimulation, this technique is often unreliable and suffers from a rapid reduction in the

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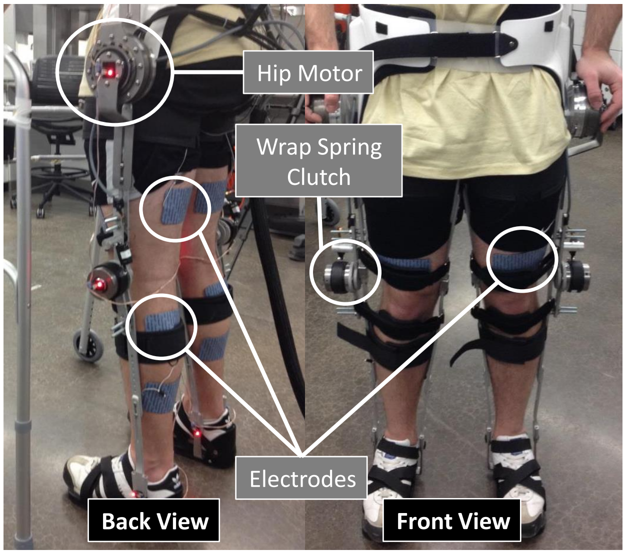

Fig. 1. SEAHO for individuals with paraplegia. Motors at the hip joints generate hip flexion/extension through position feedback control. The electrodes placed at the gastrocnemius, hamstrings, and quadriceps generate plantar flexion, knee flexion, and knee extension, respectively. When the wrap spring clutches are locked they prevent motion in the direction of flexion, but the user may always move freely in the direction of extension.

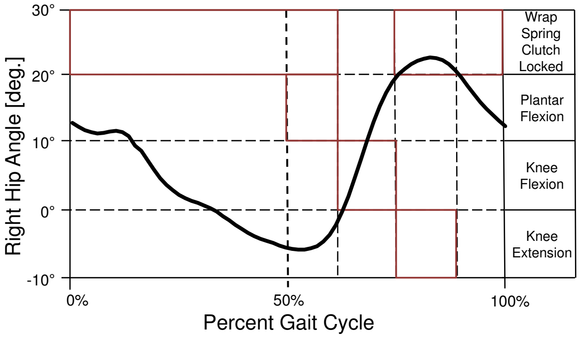

Fig. 2. The logic for the finite state machine control of SEAHO is strictly dependent on hip angle. The approximate timing of the control of the system as a function of hip angle for one full gait cycle is illustrated here. The shaded in regions indicate when a component of the system is active.

magnitude of the response due to habituation of the reflex [18]. Therefore, it was not used for the initial testing of the brace, although it may be used in future experiments with individuals with spinal cord injury to augment the torques generated by the electric motors. The hip motors were controlled using the robust integral of the sign of the error (RISE) controller [19] that is tracking a desired hip angle. The desired hip angle trajectories used for the position feedback control of this system were recorded from an able-bodied subject while taking a step. Hip angles were measured while wearing the brace, instead of normal gait hip angles, because of the movement constraints created by the brace (e.g., the brace prevents hip abduction/adduction).

SEAHO incorporates electrical stimulation of the gastrocnemius muscle, quadriceps muscle, and the hamstrings. Electrical stimulation of the gastrocnemius induces plantar flexion of the foot, which is used to help achieve push-off. By applying FES to the quadriceps and hamstrings, knee extension and flexion, respectively, can be achieved. Since knee and ankle angles were not measured for feedback control of the stimulation, a bang-bang control method was used for the control of FES. Bang-bang control has only two states, on and off. The stimulation amplitude used for each muscle was the amplitude that achieved a maximum muscle contraction. The maximum contraction stimulation amplitude was determined experimentally for the test subject. In future work, the stimulation amplitudes will be determined from an optimization of a musculoskeletal model with electrical stimulation [20]. This will allow us to use the minimal stimulation, which will result in greater walking durations.

FES was applied to each muscle group depending on where the user was in their gait cycle. To determine the user's relative location in their gait cycle, only the hip angle was measured. The relative triggering of stimulation for the quadriceps, hamstrings and the gastrocnemius muscle with respect to the hip angle was found by gait analysis data from [21], [22]. In other words, the timing for when FES is turned on and off is strictly dependent on the hip angle. The timing for FES to the three muscle groups is illustrated in Fig. 2. The regions illustrated in Fig. 2 were adjusted during the testing to achieve the best results without over-stimulating the muscles.

The final components of SEAHO are the wrap spring clutches attached at the knee joints. The purpose of the wrap spring clutch (WSC) is to prevent flexion when locked, while still allowing extension. When the WSC is unlocked, which is done using a linear actuator, it allows knee extension as well as knee flexion. This feature in SEAHO reduces the amount of stimulation required since it is not needed to maintain standing between steps or to keep the stance leg extended during a step. The WSC is only unlocked when knee flexors were stimulated, as can be seen in Fig. 2.

For the initial testing of the device only three states were used in the FSM to achieve one gait cycle. Since the user starts from standing with both feet together the first state was a half step, which transitioned the user from standing with feet together to the initial gait position. The other two states of the FSM were a state for a left step and a state for a right step. Thus, the gait cycle was achieved by pressing the button each time the user prepared to take the next step. The future device will require more control states, such as sitting to standing and standing to sitting.

RESULTS

The results of the initial testing of the hybrid device on an able-bodied subject can be seen in Figs. 4 - 5. In the first half of the gait cycle, the right leg is the stance leg. Therefore, the wrap spring clutch was locked, and no stimulation was applied to the right leg. In Region 1, which occurs from approximately 50%-65% of the gait cycle, the right gastrocnemius was stimulated to achieve heel-off.

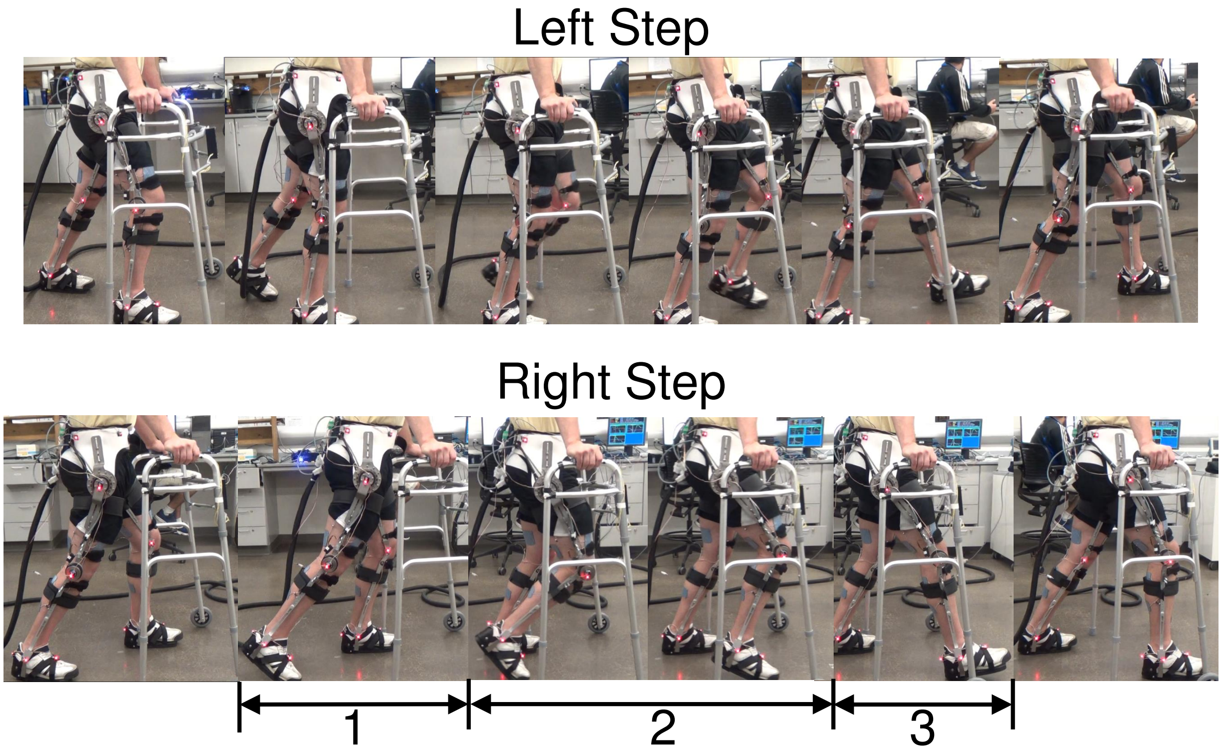

Fig. 4. This sequence of photos shows the testing of SEAHO for a full gait cycle. The top sequence of photos shows the left step, and the bottom sequence of photos shows the subsequent right step. The regions in this figure, numbered 1-3, correspond to the regions in Fig. 3.

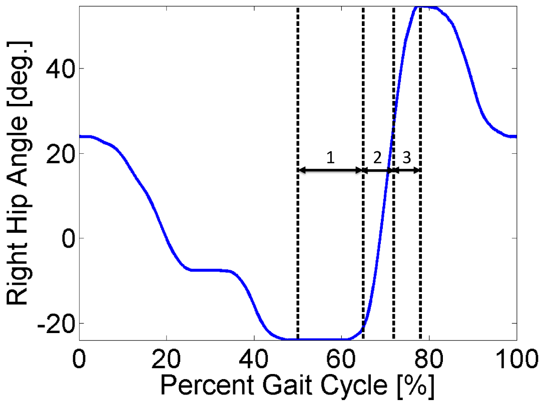

Fig. 3. The right hip angle, measured from the hip motor, and the stimulation regions for the right leg are shown for a full gait cycle. In Region 1 the gastrocnemius is stimulated, in Region 2 the wrap spring clutch is unlocked and the hamstring is stimulated, and in Region 3 the right quadriceps is stimulated.

Then, as the right hip began to flex, the stimulation of the gastrocnemius was stopped, the wrap spring clutch was unlocked, and the stimulation of the hamstrings was initiated. The stimulation of the hamstrings caused the knee to flex, which helped the foot to clear the ground. This is illustrated as Region 2 in Fig. 3, which occurred from approximately 65%-75% of the gait cycle. When the hamstrings were no longer being stimulated, the wrap spring clutch was locked again.

Note that when the wrap spring clutch is locked it only prevents motion in the direction of flexion. Therefore, although the clutch is locked the knee will still be able to extend.

Once the right hip angle had exceeded approximately 30° the stimulation of the hamstrings stops and the stimulation of the quadriceps was initiated, which caused the right knee to extend. This is illustrated as Region 3 of Fig. 3, which occurred from approximately 75%-80% of the gait cycle. Less stimulation to the quadriceps was required because once the knee is fully extended the wrap spring clutch prevented the knee from returning to a flexed position. If a measurement of the knee angle was accessible, and could be used in the control of the brace, this mechanism could be used to ensure that minimal stimulation to the quadriceps is applied.

The RISE controller, which was used for the position tracking control of the hip motors, was able to track the desired hip angles with an RMS error of 0.346° and a peak error magnitude of approximately 1.5°. As can be seen in Fig. 5, the peak RMS position tracking error for one complete gait cycle occurred at approximately 65% of the gait cycle. This corresponds to the moment when right hip flexion began, and the largest hip motor torque was required.

CONCLUSION

As a result of the capabilities of an able-bodied subject to perform multiple steps in SEAHO it can be concluded

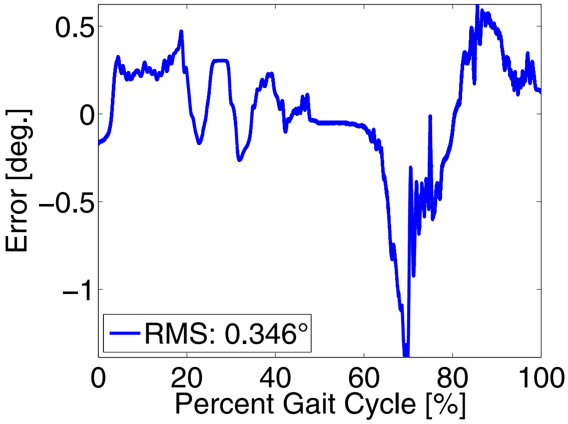

Fig. 5. The RISE controller was used for the position tracking control of the hip motors. It tracked the desired hip angle with an RMS error of 0.346° over one full gait cycle.

that the device is ready for testing on paraplegic subjects. First, inertial measurement units (IMUs) will be added to the device so that knee angle can be measured. This will allow us to implement feedback control of the electrical stimulation, which would reduce the amount of stimulation required and increase walking durations. Future plans for this research is to implement stimulation patterns that are calculated using an optimization that minimizes the amount of stimulation required to achieve an acceptable gait motion [20]. Also, as previously mentioned, peroneal nerve stimulation will be added so that hip flexion may be stimulated. This will create redundant actuation at the hip joint, which means that a control allocation problem will need to be solved. One method for solving the redundant actuator problem is to use dynamic control allocation, which will allocate control of the motor and FES based on the solution to an optimization that minimizes the sum of the motor torque and electrical stimulation.

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