Biofeedback Controlled Ankle Foot Orthosis for Stroke Rehabilitation to Improve Gait Symmetry

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ABSTRACT
Stroke affects 700,000 Americans per year resulting in the largest cause of long-term disability in the United States. Drop-foot is a common condition associated with residual disabilities of stokes and is characterized as a paralysis or weakness of the dorsiflexor muscles of the foot and ankle. The result is an abnormal gait cycle caused by the dragging of the foot and toes during the swing phase. This device attempts to incorporate key principles from Electromyography (EMG) biofeedback rehabilitation and active Ankle-Foot Orthosis (AFO) design into a single rehabilitation device. The goal is to achieve an improvement in gait symmetry between the affected and unaffected legs of stroke patients exhibiting drop-foot by providing an assisted dorsiflexion response triggered by the users own EMG signal during the swing phase. The design incorporates a modified walking brace utilizing a custom built ball-screw actuator driven by a DC motor. Surface electrodes placed over the tibialis anterior muscle of the user will record and analyze the EMG data in real-time. An EMG triggering threshold will be calibrated to each user’s ability to serve as a closed-loop control pathway for initiating the dorsiflexion response. Automatic motion capture gait analysis can be used to record markers placed on the participants lower limbs. A comparative review of the kinematics of both legs will be analyzed for symmetry during the patient’s normal gait cycle and the assisted gait cycle using the biofeedback AFO.

Keywords
Biofeedback, AFO, stroke, rehabilitation, drop-foot

1. INTRODUCTION
Stroke is diagnosed as a condition when blood flow is interrupted to any part of the brain caused by either a blockage in the artery supplying blood to the brain (i.e. ischemic stroke) or a leakage of blood from an artery (i.e. hemorrhagic stroke). According to statistics provided by the American Heart Association, approximately 700,000 Americans will experience a stroke each year. This leads to the largest cause of long term disabilities in the United States [1]. Neuromuscular dysfunctions such as hemiparesis are a common residual disability affecting stroke patients.

Human gait is defined as a manner of walking or moving on foot. It is a complex synergy of muscle coordination, timing, and balance. Gait is composed of two primary phases (i.e. a stance phase and a swing phase). It is clinically divided into 8 separate sub-phases which are (1) Initial contact (2) Loading response (3) Midstance (4) Terminal stance (5) Pre-swing (6) Initial swing (7) Midswing (8) and Terminal swing [6]. Drop-foot is a neuromuscular disorders affecting the lower limbs often related to hemiparesis which is characterized as a paralysis or weakness of the dorsiflexor muscles of the foot and ankle, resulting in the dragging of the foot and toes during gait (i.e. swing phase). This will impair normal gait functions resulting in abnormal gait patterns, higher energy expenditure, unstable gait, increased risks of falling, delayed ambulation speed, and additional physiological pathologies [12]. Patients counteract the effects by exaggerating the knee and hip flexion to provide foot clearance.

Rehabilitation therapy has been clinically accepted as an effective approach to treating neurological motor dysfunctions resulting from stroke [11]. One of the goals of rehabilitation is to retrain functional skills related to the activities of daily living (ADL) for the patient. Ambulation is considered one of the more important ADL skills to improve in order to allow the patient to have an independent lifestyle. It has been found that approximately 20% of stroke survivors will be confined to a wheelchair, and approximately 60% will have limited walking capabilities [17], usually displaying abnormal gait patterns or requiring the use of various walking aids. There are various forms of gait rehabilitation techniques available such as traditional physiotherapy, treadmill training & gait machines, functional electrical stimulation (FES), and electromyography (EMG) biofeedback. Traditional physiotherapy is the most common form of rehabilitation which involves the cooperation of a physical therapist working consistently with a patient to improve functions such as strength, range of motion, and reduction of spasticity [12,13]. The downside to this approach is the related high cost and the necessity of a trained specialist [11]. Treadmill training and gait machines have the advantage of allowing patients to perform repetitive functional specific tasks while under the supervision of a physical therapist and/or a body-
2. BIOFEEDBACK AFO DESIGN

2.1 Hardware Design

2.1.1 AFO Brace

A standard AFO is commonly an L-shaped brace constructed out of a plastic polypropylene material [15] that is worn inside the user’s shoe. The design traditionally requires some custom fitting to the particular user and the material itself provides a semi rigid frame which offers some level of flexibility and passive movement. The standard AFO was not chosen because of the need for a more universal fitting to a variety of possible research participants; in addition a more rigid frame is needed for attaching additional mechanical and electronic components while still providing free ankle motion.

The brace selected to serve as the frame of this AFO device was a Procare – Pro-Rom Walker (Model 79-95045) [16]. The brace is a lightweight, low-profile design with a non-skid rocker bottom sole. Its intended design was for use as a support walking cast after achilles tendon repair, stable fractures of the lower leg and ankle, acute ankle sprains and soft tissue injury. It was selected because of its inherent walking functionality design, built in metal supports and ankle hinge, and comfort factor. The device has a total Range of Motion (ROM) of 30° dorsiflexion and 45° plantarflexion.

2.1.2 Ball Screw Actuator

A ball screw actuator with a custom built housing frame will provide motion to the overall design. This type of actuator incorporates ball bearings enclosed in a re-circulating nut surrounding a screw shaft design. They translate rotary motion into linear motion or vice versa. Ball screws have a low coefficient of friction which reduces the impedance and increases the ability to back-drive the device (i.e. ability to move in a linear direction by providing a low axial load when the device is disengaged from its power drive). This is ideal for the biofeedback AFO which requires dynamic free motion during the various gait phases and its ability to provide minimal resistance to user voluntary motion.

Specific equations are used to calculate the necessary load and speed parameters of the ball screw and rotary drive motor to meet functional requirements. A maximum operating load of 30 lbf was selected as an educated estimate of the force required to counteract the natural resistance in the antagonistic muscles (due to mild spasticity) and equipment, necessary to dorsiflex the ankle. A linear travel speed of 4 in/sec was selected as a suitable requirement for the actuator to reposition the ankle in the proper position during the swing phase considering average ankle motion during stride and walking speed [8]. Using the following equations, parameters for ‘n’ and ‘T_d’ are calculated.

Equation 1:

\[ n = \frac{\text{Travel rate}}{P} = 1,524 \text{RPM} \]

Equation 2:

\[ T_d = \frac{FP}{2\pi e} = 0.177FP = 1.11\text{lbf-in} \]

A total travel length of 6.5 inches of the ball nut assembly provides a 20° dorsiflexion and 40° plantarflexion ROM for the device. These parameters are slightly below the average complete ROM for a normal adult ankle, but allows adequate ROM for the limits encountered during a gait cycle.
2.1.3 DC brush motor

A standard brush type DC motor will be selected based on the value of ‘n’ and ‘Td’ calculated previously. The selected motor should have parameters slightly exceeding the calculated values to provide performance within the operating boundaries of the motor itself. The DC motor provides the rotary motion necessary to power the axial movement of the ball screw. However, when the DC motor is inactivated, it provides minimal impedance allowing the shaft to rotate freely with a low application of axial force to the ball screw assembly (i.e. back drive). Figure 1 below provides an illustration of the custom built ball screw actuator unit with the attached DC motor, drive couple, and piston drive assembly.

2.1.4 Incremental Encoder

A rotary incremental encoder is necessary to provide feedback as to the position and motion of the ankle at all times. A quadrature encoder was selected to provide position and directional movement (i.e. dorsiflexion vs plantarflexion) of the ankle. The encoder is positioned in line with the axis of the ankle hinge joint on the lateral side of the right leg.

Figure 2 shows a basic illustration of the complete AFO design including the walking brace, ball screw actuator unit, and incremental encoder.

The encoder will provide input as to whether there is movement in the ankle and when the desired dorsiflexion position is obtained by either the user or the assistive mechanism. The device will not activate unless it determines that there is no relative motion achieved or only plantarflexion during the initial swing phase of gait.

2.1.5 Load Cell

Two load cells will be incorporated into the sole of the AFO brace; positioned in the forefoot and heel of the device. They will provide input to determine when the user is in the stance phase versus the swing phase of gait. The AFO will assist the user to dorsiflex their ankle only during the swing phase of gait.

2.1.6 EMG recording device

A portable EMG measuring equipment will be incorporated into the control system input. There are various commercially available EMG devices [5,18], but a final device has not yet been selected. Standard surface electrodes will be placed over the tibialis anterior muscle of the user to record muscle activity related to the dorsiflexion of the ankle. The EMG signal will be calibrated to the EMG output ability of the user to operate the device.

2.2 Software Design

2.2.1 System architecture

The basic architecture for this device will incorporate four separate inputs and one output. Figure 3 provides a basic schematic diagram of the entire system.

The four inputs include (1) the EMG reading from the surface electrodes, (2) the incremental encoder, (3) forefoot located load cell, (4) heel located load cell. The inputs will be integrated into a controller board. The controller board can be programmed via a host computer with various logics for handling the input data. The output is directed to the DC motor which will either be instructed to remain inactive or provide motion to initiate the dorsiflexion response.
2.2.2 Design function

The function of the biofeedback AFO is to serve as a secondary "assistive" device in providing a dorsiflexion of the ankle when the user is unable to voluntarily provide the same motion. Therefore, if the user has the capability to generate enough neuromuscular control to voluntarily dorsiflex their ankle, the device remains inactive and minimizes impedance in the system. The biofeedback AFO will assist the user for the following two circumstances. (1) when the user generates a voluntary EMG signal in an attempt to raise their ankle, but no dorsiflexion motion is registered during the initial swing phase, and (2) when the user enters the initial swing phase and no voluntary EMG signal is detected. The second circumstance serves as a fail-safe procedure to prevent unstable gait patterns caused by unwanted contact of the toe and foot resulting from drop-foot.

Although patients with hemiparesis may not be able to generate an EMG signal with enough intensity to create a voluntary contraction, there is still residual EMG signaling to the affected muscles. Calibration of the device to the user will consist of recording the maximum EMG signal capable by the patient. A threshold equal to the maximum capacity recorded will be set as the activation trigger. This trigger will serve as the signal to the AFO device that the user is attempting a voluntary movement. By encouraging the user to re-create similar intensity EMG outputs will help re-train the user to improve their neuromuscular control. Positive reinforcement is provided by the artificial dorsiflexion movement of the ankle.

The two load cells positioned at the forefoot and heel of the sole help to determine what phase of gait the user is in. When no load is detected in both sensors, represents the beginning of the swing phase when the affected leg is advanced forward with no weight being supported. This coincides with the initiation of the sensory phase where the EMG signal and incremental encoder inputs will be analyzed to determine whether a response is needed. When the foot makes contact with the floor during the terminal swing phase, the load cells will again register an input which signals the end of the sensory phase.

3. TEST METHOD

Gait analysis is the study of the walking gait and is commonly used by medical professional as a clinical tool to help in the diagnosis and treatment of abnormal gait. Kinematics is a category utilized in gait analysis which investigates positions, angles, velocities, and accelerations of body segments and joints during motion without the incorporation of forces [19].

Two separate tests will be conducted during this portion of the research. Volunteer stroke patients with drop-foot disability will be selected based on the following criteria: (1) participants will have been clinically diagnosed of having a stroke more than 6 months prior to participating in this research study, (2) only those participants with hemiparesis drop-foot caused solely by a single incident of stroke will be selected. (3) Individuals with additional neurological disabilities caused by other conditions or multiple strokes will be further excluded. (4) participants must currently be able to walk a distance of 5-10m on their own with or without a lower leg brace. (5) approval granted by their personal physician. (6) exhibit minimal spasticity in their lower limbs.

The gait walking tests will be performed in a controlled environment. Motion capture video gait analysis will be used to record the gait kinematics [6,8]. Four reflective markers will be placed on the anatomical landmarks of the participant’s leg including the greater trochanter, epicondyle, lateral malleus, and fifth metatarsal base of both legs. Three video cameras (model: JVC DVL 9800) will be positioned to the front and sides of the walkway to capture the sagittal and transverse plane movement of the participant. A complete gait cycle of each leg will be recorded during each pass (Figure 4).
comfortable for them. The motion is captured and recorded on film to be analysed at a later time.

The second walking test (i.e. “assisted test”) will include the participant walking the same 5 m distance through the designated walkway using the biofeedback AFO. This test will represent the walking pattern as a result of assisted dorsiflexion control. When the individual is ready, the video cameras will be re-activated and the participant is asked to walk from the start to the end point again at a casual pace that is comfortable for them. The motion is captured and recorded on film to be analysed at a later time.

The APAS (Ariel Performance Analysis Systems) software will be used to digitize the video data for analysis. The following kinematic data will be gathered from the gait analysis.

- Gait velocity
- Gait symmetry
- Stride length
- Step length

A comparative kinematic analysis will be performed between the assisted and unassisted gait patterns of the volunteer stroke patients to determine if there is an improvement in gait patterns when utilizing the biofeedback AFO. The data between the various participants and tests will be normalized by comparing just a single gait cycle (i.e. initial contact – initial contact) for each leg.

4. ACKNOWLEDGMENTS

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5. REFERENCES


