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ROBOTIC SHOE: AN ANKLE ASSISTIVE DEVICE FOR GAIT PLANTAR FLEXION ASSISTANCE

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ABSTRACT

Gait disorders can be attributed to a variety of factors including aging, injury, and neurological disorders. A common disorder involves the ankle push-off phase of an individual's gait, which is vital to their ability to walk and propel themselves forward. During the ankle push-off stage, plantar flexor muscles are required to provide a large amount of torque to propel the heel off the ground, thus a condition that compromises the strength of these muscles can greatly affect one's walking ability. In order to rectify these issues, Ankle-Foot Orthoses (AFO) are used to provide support to a user's ankle and assist with the force needed for heel off. This article introduces a robotic AFO which was developed with the intent of aiding during the heel-off stage. The proposed design utilizes the user's body weight to extend constant force springs positioned parallel to the calf to replicate the muscular force generated in plantar flexion. The extended spring is held in place using a ratcheting mechanism which is released with a solenoid during heel up. Similar research has been conducted in which assistive AFO's have been created, however little research has investigated the use of constant force springs in such devices. A healthy user tested the device on a treadmill and surface electromyography (sEMG) sensors were placed on the user's plantar flexor muscles to monitor potential reductions in muscular activity resulting from the assistance provided by the AFO device. The data demonstrates the robotic shoe was able to assist during the heel-off stage and reduced activation in the plantar flexor muscles was evident from the EMG data collected.

Keywords: AFO, assistive devices, plantar flexor weakness, heel off, constant force spring, rehabilitation, gait assistance, treadmill

INTRODUCTION

Those most commonly affected by gait disorders are the elderly, with about 10% struggling from ages 60-69 and more than 60% of people affected aged 80 years and older [1]. In addition to age, neurological and trauma-related injuries can have a significant effect on one's walking ability [2] [3]. Having the ability to assist a stroke patient's gait would not only improve their ability to walk but would also be instrumental in rehabilitation to help them regain locomotion.

To understand the issues that patients with gait disorders face, one must investigate the mechanics of a healthy gait cycle. As seen in figure 1, a gait cycle involves several stages which work in concert to propel a person forward. The first stage of the gait cycle begins with the heel strike, where the subject makes heel contact with the ground and proceeds to foot-flat and mid-stance. The second stage is heel off, in which the subject first begins to lift their foot off the ground. This paper will focus on developing a solution to improve the heel off stage of the gait cycle. Once the heel is off the ground, the subject lifts their toes and enters the swing phase. After the user fully swings their foot forward and their heel contacts the ground, the gait cycle is completed [4].

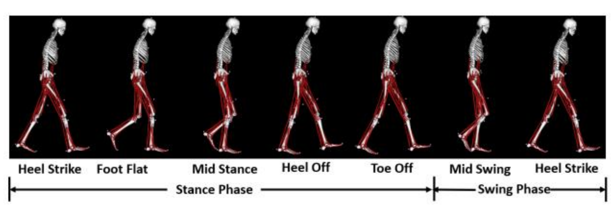


Figure *1:* GAIT PHASES (REFERS TO MODEL'S RIGHT FOOT)

Throughout the gait cycle leg muscles are constantly working to propel the subject forward, with the most work intensive stage being the heel off stage. This can be attributed to the fact that the ankle joint accounts for 35-45% of the total mechanical work during each stride [5]. This work intensive motion results in a required torque of 1.73Nm per kg of body mass [6]. To assist with the work done during the heel off stage, research has been conducted to develop wearable devices that can reduce the load required by the plantar flexor muscles. These systems are known as assistive AFOs and are either active, passive, or a combination of the two such as the device discussed in this paper. Passive AFOs are typically lighter than their active counterparts, as they function without the use of an actuator [7-8]. These devices utilize the user's body weight to store energy in a spring and a mechanical system to release the stored energy during the heel-off stage.

As a downside, passive devices are only able to operate on the finite amount of energy provided by the user's body weight. This energy is generally stored in a linear spring positioned parallel to the user's calf. The springs reach their maximum energy state once fully stretched, occurring when the user's heel is flat on the ground. However, the calf muscles are also stretched when the foot is flat on the ground [10]. This is suboptimal for assistance because it results in minimal force being applied at the end of the heel-off stage, when the patient needs the maximum force. Also, such devices are not nearly as functional when the user does not begin their gait cycle with their heel on the ground.

On the other end of the spectrum, active AFOs are ideal for providing ankle assistance in a controlled manner. They are also very effective in applying enough torque to reduce muscular activation required during heel off. It is common for these devices to utilize compressed gas or electric motors as a means of applying support to the heel [9] [14]. The actuators used on active devices add weight—usually over 1kg—which can further affect one's gait. These active devices also require an external power source such as a battery or a gas tank in order to function. If the actuator requires a significant amount of energy to assist, these power sources will need to be replenished after few actuations. This would make the device impractical when used outside of a laboratory environment.

This paper explores a semi-active system that aims to combine the lightweight characteristics of a passive AFO with an active release mechanism that allows for more controllable and reliable assistance during heel off. This design will additionally make use of constant force springs that will allow for continual force throughout the entire heel up motion. In doing so, the constant force spring will be able to provide force as the plantar flexor muscles are fully contracted, thus at their weakest

1 ROBOTIC SHOE DESIGN

The objective of our research is to design a semi-active AFO with the following properties:

1. Provide assistive force during the heel-off gait phase.
2. Allow for the device to be used with a variety of shoe sizes up to men's size 12.
3. Be able to supply force throughout the entirety of the heel up phase
4. Add less than 1kg to the user's foot.

FIGURE 2: ROBOTICS SHOE

The robotic shoe functions using a constant force spring and a ratcheting mechanism that stores energy supplied by the user. The energy released upon heel off which is monitored using shoes capable of measuring ground reaction forces. This section is divided into three parts: A description of the locking mechanism, frame design and spring selection, as well as the sensors and control method of the robotic shoe.

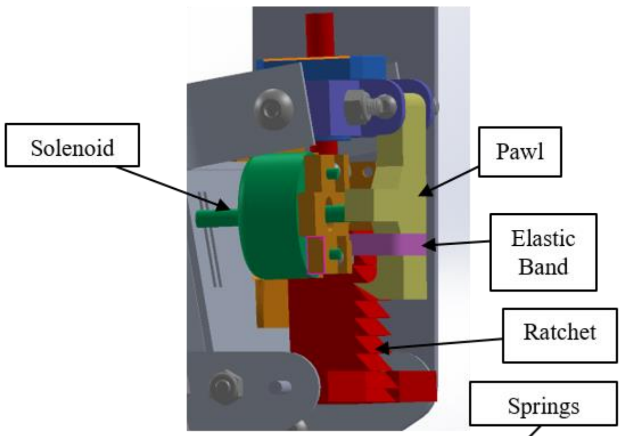
1.1 LOCKING MECHANISM

The locking mechanism proposed in this paper is positioned on the back of the device. This evenly distributes the force throughout the frame to prevent the frame from twisting. Figure 3 illustrates how the pawl is held in place with elastic bands which pull the pawl against the ratchet. This allows the pawl to lock into place without requiring assistance from an actuator. This design helps to reduce power consumption as the actuator will only need to be powered while the device is unlocking. The pawl and the ratchet were machined out of 6061 aluminum so as to increase the longevity of the device.

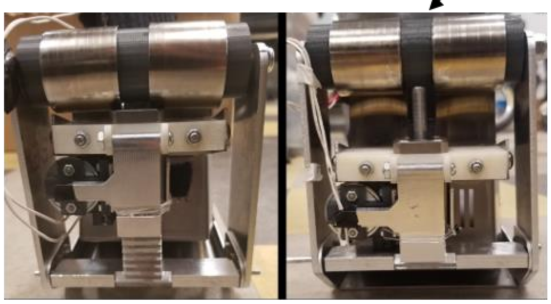
The selected solenoid is a Ledex 2EC push pull solenoid, which is capable of outputting 30N of pushing force at 3mm from its extended position. This solenoid was selected because it is able to travel the required 3mm in less than 10ms. In addition, utilizing a 1300 mAh LiPo battery, the solenoid can theoretically be used for 5.4 hours at a walking speed of 1m/s.

1.2 FRAME AND SPRING

The frame was designed to fit athletic shoes that are less than 94.675mm wide or up to men's size 12. It consists of a rotating plate that the foot is placed into, as well as a base plate which is stationary. The two plates are made of 5052 aluminum. As Figure 4 indicated, a finite element analysis study was conducted on the frame to confirm it will be able to support a user at 90kg.



a) Robotic Shoe CAD



b) LOCKING MECHANISM DESIGN UNLOCKED (LEFT) V.S. LOCKED (RIGHT)

FIGURE 3: ROBOTIC SHOE LOCKING MECHANISM

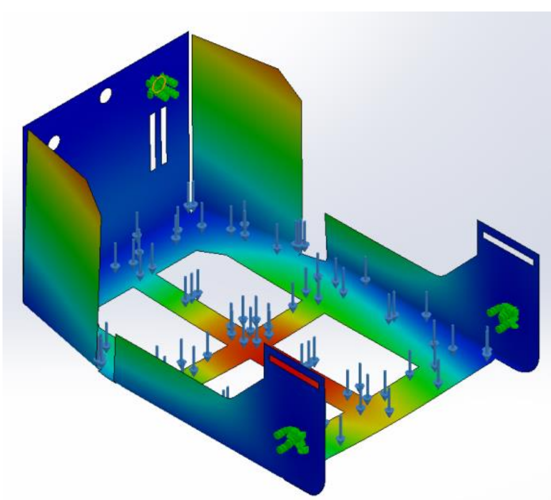


FIGURE 4: FORCE ANALYSIS OF FRAME

The spring selected is a constant force spring which provides 6.7kg of force. A single spring was cut to create the two springs mounted on the device, resulting in a theoretical 13.4kg of force and 17.03Nm of torque. In total this accounts for 11% of torque required for a 90kg user. Through the heel up phase the device can do 4.75J of mechanical work. A constant force spring was selected as it can provide a force throughout the entire heel up gait cycle as compared to a linear spring which would only provide assistance during the initial moments of heel off. Muscular biokinetic research was performed, which indicated the muscles in a leg work as a non-linear spring and can store more energy when they are elongated [13]. In addition, a constant force spring will allow for a basic control system as the force provided can be easily modeled throughout the entire gait cycle. The constant force spring also provides the same amount of force at each of the different locking positions compared to a linear force spring which would not provide as much force when the foot is not fully flat.

1.3 SENSOR AND CONTROL

To accurately determine the actuation timing, the robotic shoe utilized a "smart shoe" which can monitor the user's ground reaction forces, as shown in Figure 5. The smart shoe utilizes four coiled tubes that are connected to pressure sensors. These sensors are located on the shoe to gather pressure data from the heel, toe, metatarsal 1 (Meta 1), and metatarsal 4 (Meta 4) areas of the foot. When the user applies their body weight onto one of these coils, the pressure inside the tubes change and recorded with the sensors [11].

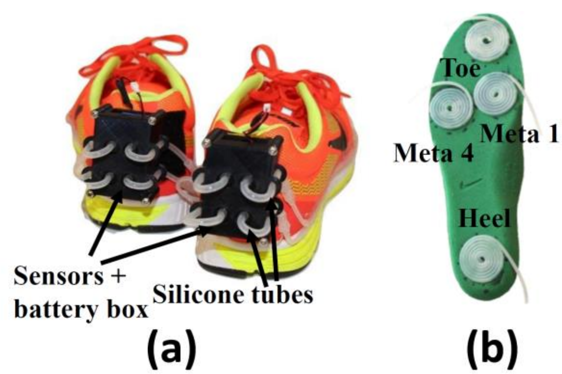


FIGURE 5: (a) SMART SHOE SENSOR BOX, AND (b) INSOLE

The pressure sensor signals from the shoe are collected by an In-Situ Intel Edison microcontroller on the smart shoe and sent via WiFi to a Raspberry Pi that is used to control the robotic shoe. Once received by the Raspberry Pi, the shoe's sensor data is filtered using a Finite Impulse Response filter routine to reduce any sensor noise. This filtered data is then used to determine the shoes responses of the sensors located at Meta 4 versus that located at heel.

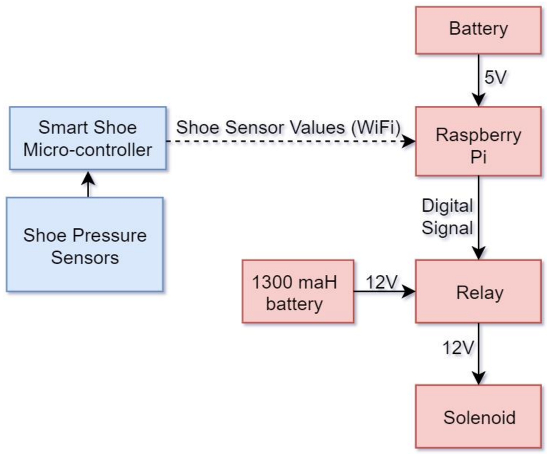


FIGURE 6: ELECTRICAL BLOCK DIAGRAM

At the data point where the heel sensor pressure is less than the average pressure from the Meta 1 and Meta 4 sensors, a digital high signal is sent by the Raspberry Pi to a relay controlling a solenoid which drives the unlock cycle of the ratchet mechanism. Unlatching the ratchet releases the stored spring energy and assists in the upward motion of the heel. After the spring is fully retracted, the Raspberry Pi releases the relay and solenoid to repeat the cycle. Figure 6 overviews the control procedure of the device.

2 TESTING

The device was tested on an unimpaired 178cm and 68kg male subject who wore a size 10 of the smart shoe. The subject walked on a Bertec dual belt treadmill (Columbus, OH) with integrated force plate both in two phases. The test was repeated once with the robotics shoe on and once with it off. The experiments were done at the speed of 0.6 m/s. To measure muscle activities, surface electromyography (sEMG) sensors were placed on the major plantar flexion muscles, the Gastrocnemius and Soleus [12]. The exact locations of the sEMG sensors can be seen in Figure 7.

3 RESULTS

In order to quantify the results, the sEMG sensors and force plate sensor data was imported into MATLAB. The force plate data was filtered using a low-pass filter and the toe-off event for each step was calculated. The use of these data points allowed for the identification of each step's stance phases. The sEMG sensors data was filtered using a moving average filter with a window of 300 data points and is also segmented into each step's stance phase. Each step's stance phase is then averaged to identify the average sEMG response. In addition, the root mean squared (RMS) value and maximum sEMG peak values for the average sEMG reaction was calculated.

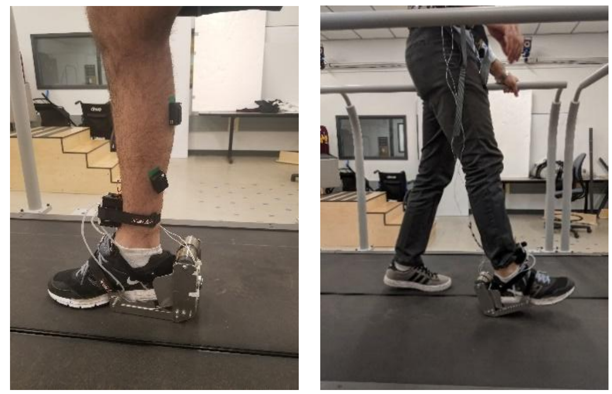


FIGURE 7: SUBJECT WALKING ON TREADMILL WITH THE ROBOTIC SHOE (LEFT) AND EMG PLACEMENT (RIGHT)

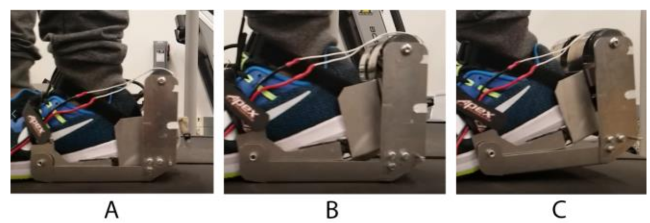


FIGURE 8: (A) MIDSTANCE (B) HEEL OFF BEGINNING (C) HEEL OFF ENDING

The data in Figure 9 shows a reduction of 5% sEMG peak value in the Gastrocnemius muscle and a reduction of 24% for the Soleus muscle during the assisted walking versus the non-assisted walking trials. The RMS values indicate a reduction in muscular energy exhausted. This reduction was 30% for the Gastrocnemius and 38% or the Soleus between the non-assisted walking and the assisted walking trials.

The sEMG graphs shown in figure 11 and 12 of the Soleus and the Gastrocnemius show a trend in which the ground reaction forces are delayed resulting in a shifted peak between the assisted trials compared to the normal walking trial. This can be possibly attributed to the weight of the device delaying the activation of the Soleus and Gastrocnemius muscles as they are not required to activate until the robotic shoe has reached its maximum angle of assistance, at which point the muscles must activate to complete the lifting of the foot and swing forward.

4 DISCUSSION and FUTURE WORK

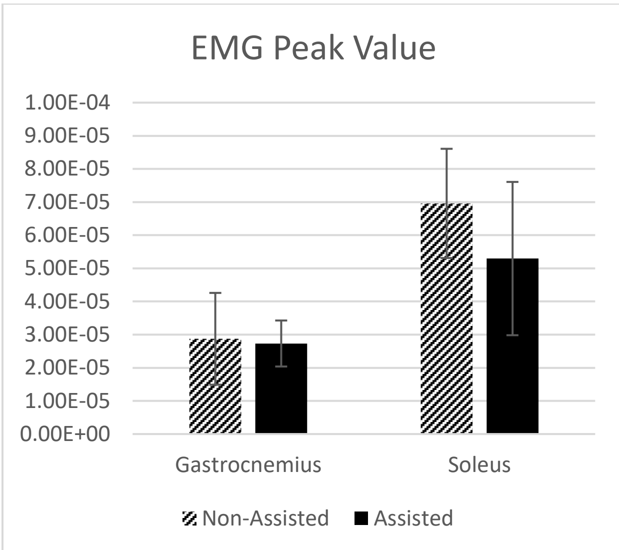


FIGURE 9: EMG PEAK VALUES

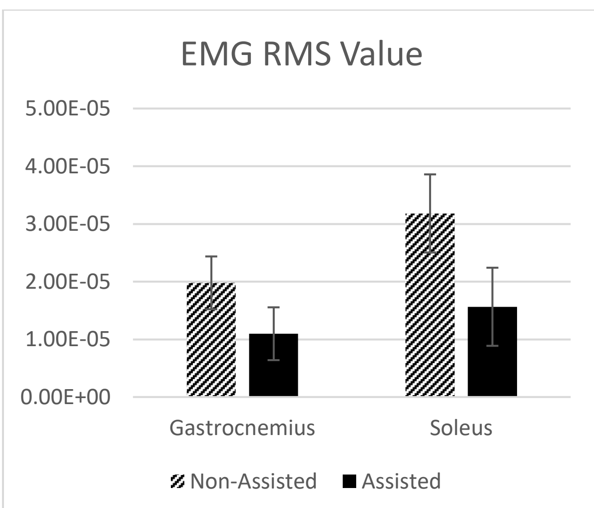


FIGURE 10: EMG RMS VALUES

This device still faces several challenges. Firstly, like most passive assistive AFOs, it is only able to provide assistive force based on the spring that is used in the system. In the future, we would like to implement a solution that involves controlling the assistive spring force applied to the ankle. Also, it was observed that because of the elongation of the device in swing phase, users had to slightly modify their swing phase gait pattern. Therefore, an assessment of ground clearance and potential changes to swing phase kinematics needed to be performed. Next, we would like to conduct further research in the control system used to determine the unlocking timing of the device. This will make the force applied to the user feel more natural as the unlocking will be able to integrate seamlessly into the user's gait cycle. Finally, additional effort should be made to further reduce the weight of the device. Integrating the assistance directly into a shoe would make the frame obsolete and significantly reduce the weight of the robotic shoe. The work conducted in this paper along with the suggested modifications could result in an effective assistive AFO. Besides functional changes the evaluation of the device is still quite limited. More comprehensive testing will need to be completed on healthy as well as impaired subjects to gather additional evaluation data to further determine the effectiveness of the device.

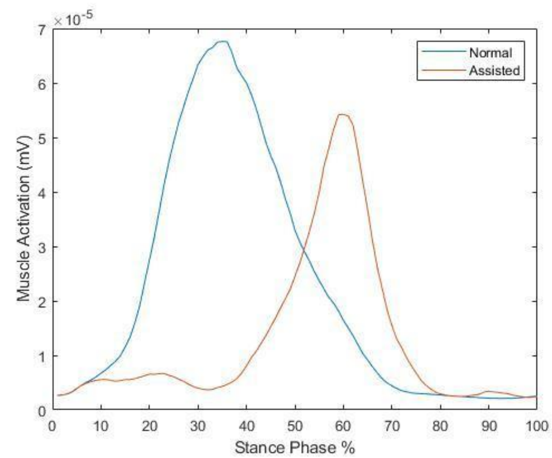


FIGURE 11: SOLEUS EMG CURVE

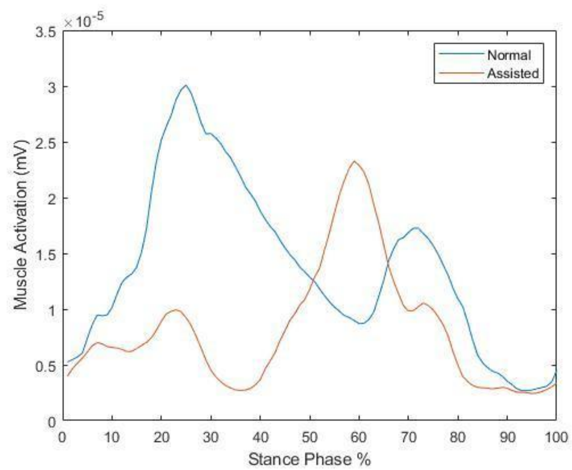


FIGURE 12: GASTROCNEMIUS EMG CURVE

5 CONCLUSION

Assistive AFO's and robotic shoes are extremely useful and can help thousands of people with gait disorders. The robotic shoe discussed in this paper provided very promising results regarding the future of this technology. The constant force springs generated uniform force through the entire gait cycle and did not rely upon the user to fully plant their feet flat when walking. This would eliminate the constraints of only being able to operate the device on a flat surface. In order to justify the success of the device, a sEMG sensor was used to monitor the walking activity. The result of the sEMG test showed that the device could provide assistance during the heel off phase.Utilizing the smart shoe's ground reactant force sensors proved to be a reliable way to actuate the device in a timely matter. As this research is continued, we hope to further improve the control systems of this device as well as its mechanical abilities.

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