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An Assistive Ankle Joint Exoskeleton for Gait Impairment

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Abstract. Motor rehabilitation and assistance post-stroke are becoming a major concern for healthcare services with an increasingly aging population. Wearable robots can be a technological solution to support gait rehabilitation and to provide assistance to enable users to carry out activities of daily living independently. To address the need for long-term assistance for stroke survivors suffering from drop foot, this paper proposes a low-cost, assistive ankle joint exoskeleton for gait assistance. The proposed exoskeleton is designed to provide ankle foot support thus enabling normal walking gait. Baseline gait reading was recorded from two force sensors attached to a custom-built shoe insole of the exoskeleton. From our experiments, the average maximum force during heel-strike (63.95 N) and toe-off (54.84 N) were found, in addition to the average period of a gait cycle (1.45 s). The timing and force data were used to control the actuation of tendons of the exoskeleton to prevent the foot from preemptively hitting the ground during swing phase.

1 Introduction

Drop-foot, also known as foot drop, is a common affliction that frequently occurs due to injury to the peroneal nerve, disrupting the gait cycle [1, 2]. The gait cycle for walking can be categorized into four phases, namely the stance phase, swing phase, heel-strike, and toe-off [3]. If the drop-foot is caused by a stroke or other neurological disorder, it could become a lifelong disability that needs continuous treatment [4]. In this case, ankle foot orthoses (AFOs) are usually worn to support walking to reduce the risk of falling. However, those currently commercially available are not active assistive technologies; they simply keep the ankle joint angle close to 90°, preventing the foot from unnecessarily hitting the ground while walking [5, 6]. They reinforce a pattern of nonuse by restricting joint position and movement, causing atrophy of the muscles and abnormal gait patterns [5, 7–9].

Due to these limitations, exoskeletons/exosuits are considered as an alternative to traditional AFOs. However, these rigid exoskeletons are often heavy and require extensive power, while having short battery life. Current AFOs and exoskeletons on the

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market are neither capable of raising the foot fast enough, adjusting to changes in walking speed, nor capable of coping with variations in gait (such as sharp turns, *etc*.). Soft exoskeletons can address these issues, but none are currently available and can cope with varying gait patterns.

This paper proposes a low-cost, soft assistive device for gait assistance for drop-foot. The methodology including the hardware components, electrical components, and experimental methods will be presented in Sect. 2, and the results of the experiment in Sect. 3. Section 4 will cover the limitations, and future work of the device. A brief conclusion will be presented in Sect. 5.

2 Methodology

2.1 System Architecture

The proposed design is composed of two main elements:

(1) *The tendon-based actuation mechanism powered by a DC motor;*
(2) *A 3D printed insole connecting the tendon anchors to a shoe and housing the pressure sensors.*

The Tower Pro MG995 (Tower Pro Pt Ltd., Singapore) was used as the actuator and a Bowden cable was anchored at the shoelaces by a 3D printed anchor piece connected to the printed shoe insole via Velcro straps. It ran across the top of the foot and up the shin where it was attached to the motor located below the knee (as shown in Fig. 1). A three-dimensional model of the insole was designed using SolidWorks, and was customized to fit the Gel-Venture 6 (Asics, Japan) trainer. This model was printed with ABS using the Fortus printer 450MC.

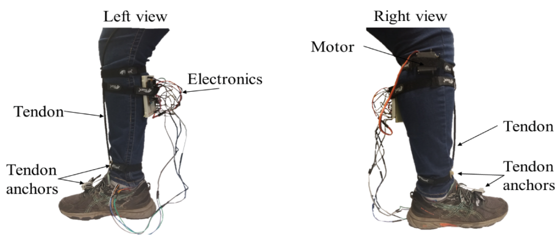

Fig. 1. Side views of the prototype of the proposed low-cost assistive ankle device worn on the right leg with both the circuit and motor shown. The tendon is attached to an anchor point above the shoelaces and at another point at the ankle before attaching to the motor worn on the shin.

2.2 Electronics and Processing

The system is integrated with two FlexiForceTM A502 sensors (Tekscan, United States) for measuring forces exerted by the foot on the ground during walking and the Arduino Uno (Arduino, Italy) is used as an embedded microcontroller.

2.3 Experiment

To get baseline readings of the two force sensors, a 75 kg subject walked for 30 s (repeated 10 times). The subject was asked to walk at a slower pace to mimic the gait pattern of someone who suffers from drop-foot.

2.4 Control

From the baseline reading data, the maximum force of the heel during heel-strike and the toe during toe-off were found for each step. The baseline data were also used to determine the threshold ranges for detecting the heel-strike and toe-off events in order to initiate actuation of the tendons. Thresholds were manually determined by initially classifying the training data into four categories: heel-strike, mid-stance, toe-off, and swing.

For both heel-strike and toe-off events, the information from the toe and heel sensors fell into two Gaussian distributions, with some overlap at the tails. The threshold was set at two standard deviations away from the means of the distributions in order to capture 95% the two distinct thresholds. This information was used to determine the timing of an average step, which combined with the average force data to determine when to activate the motor, and how fast to pull the tendons. The motor control function is presented as the pseudo code below.

1 <u>function motor control</u> (h ,t);
Input: Force on heel sensor *h*,
    Force on toe sensor *t*,
    Where, h >= 0 and t >= 0
Output: The motor control for two circumstances,
toe-off (*to*) and heel-strike (*hs*)
2 $f(h, t) = e^{-\{\frac{(h-\mu_h)^2}{2\sigma_h^2} + \frac{(t-\mu_t)^2}{2\sigma_t^2}\}}$
3 initialize motor starting position;
4 **if** $\mu_{to}^t - 2\sigma_{to}^t$ < t < $\mu_{to}^t + 2\sigma_{to}^t$ **and** h < $\mu_{to}^h + 2\sigma_{to}^h$ **then**
    increment motor angle;
    time delay;
5 **else if** t < $\mu_{hs}^t - 2\sigma_{hs}^t$ **and** h < $\mu_{hs}^h + 2\sigma_{hs}^h$ **then**
    decrement motor angle;
    time delay;
    end

3 Results

By using the integrated FSRs in our experiments, we found that the average maximum force for heel-strike and toe-off are 63.95 N, 54.84 N, respectively, which are then used to determine the parameters for the motor control. The temporal difference between toe-off and heel-strike was then calculated to determine the period of the swing phase. On average, the swing phase lasted approximately 1.45 s. This information was used to control the motor to actuate after toe-off and heel-strike, thus preventing foot drop or toe slap. After detecting toe-off, the motor takes 1.2 s to complete a 20° rotation in the clockwise direction, lifting the toe upward into dorsiflexion, preparing the heel for heel-strike. Then, after heel-strike is detected, the motor takes 1.2 s to complete a 50° rotation in the counter-clockwise direction, preparing the toe for toe-off. The time was chosen empirically as 1.2 s to ensure that the foot is in the correct position before the gait event (toe-off or heel-strike).

4 Discussion

In this paper, we proposed an assistive ankle joint exoskeleton and demonstrated its potential to be as a low-cost solution for providing assistance to stroke patients with drop-foot. The design is lightweight and does not restrict ankle movement, thus addressing the limitations of rigid exoskeletons/exosuits. However, the current prototype will require further development before it can be deployed as a gait assistive device. In this preliminary stage, the main limitation of the proposed device is its reliance on the wired control. As a next step, a wireless microcontroller that utilizes Bluetooth could be used to enable wireless connection and eliminates the need for tethered wires, allowing for more portability. Additionally, integrating inertial measurement units and applying machine-learning algorithms can improve the control mechanism to enable the exoskeleton to adapt to variations in gait. The methods presented could be used as a platform for a regression-based machine learning approach to identify real-time changes in gait speed to provide variable actuation speed with variable walking speed.

5 Conclusion

Drop-foot is a common condition that could affect anyone, but often occurs after a stroke. While there are commercially available assistive and rehabilitative devices that target drop-foot, none can account for varying gait patterns. Therefore, this paper proposed an assistive ankle joint exoskeleton for stroke rehabilitation with the potential to account for varying gait patterns. Although the primary target population for the proposed device is stroke survivors with drop-foot, its potential reach can be of great value to other patients. This includes providing gait assistance for those recovering from peroneal nerve injury, and assisting people with other neuromuscular disorders.

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