Personalized Gait Treatment Using Passive Controllable Ankle Foot Orthosis

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Abstract. Ankle Foot Orthosis (AFO) is usually prescribed for gait treatment. Low cost, easy to fabricate, safe, long term usage, and personalized AFO is demanded to facilitate and accelerate the prescription process, which is iterative, individualized, and collaborative. Passive Controllable AFO (PICAFO) was developed to fulfill the demand, consisting of several research works, such as the gait detection method, smart actuator design, and controller development. Two gait detection methods had been considered. Firstly, the system utilized the Electromyography (EMG) biosignal to detect the stance and swing phase. Secondly, hybrid Magnetorheological Elastomer (MRE) is used to detect four gait phases based on foot contact. The smart actuator, a small scale Magnetorheological (MR) brake, had been constructed, which generated 2.1 Nm maximum damping stiffness to partially support the ankle stiffness. The controller is essential because controlling the damping stiffness accordingly to the current gait ensures positive assistance. The latest version of the PICAFO controller utilized ankle velocity reference to control the MR brake stiffness, which can be estimated based on the user's walking speed and body mass index. The presented research works show that achieving personalized gait treatment using the PICAFO system is possible.

1. Introduction

Nowadays, science fiction movies convey to us that the robotic field is effortless. Ironman suit enables Tony Stark to perform the unhuman movement [1]. For instance, the thruster at the foot palm allows him to float and fly in the sky, lift a heavy object, and even shoot a laser beam. The helmet is not merely a decoration, where he can-do real-time communication with an Artificial Intelligence (AI) called JARVIS that provides important suggestions during a hectic scene. There is also an Arc reactor as the power supply that lasts long despite the small dimension. Given that many kinds of Ironman technologies, the suit can still fit into a small suitcase and be worn in a second. Meanwhile, the reality is harsh. The development of such a sophisticated robotics suit requires many efforts and dedication, but the current result is still far from perfect.

In the walking gait rehabilitation field, the robotics technology improves current equipment, such as Ankle Foot Orthosis (AFO) [2]. The AFO is a solid leg brace that covers the foot until the calf. AFO is designed to assist walking gait around the ankle by locking the foot plantarflexion, preventing foot drop on post-stroke patients. After the effect of AFO usage is shown in Figure 1. The post-stroke patient initiates the foot contact on the heel (solid grey line) instead of the toe (black dash line). Preventing foot
drop is just one small part of a complex quasi-periodic system, such as walking, but it is a critical function that increases walking stability. In other words, it reduces the probability of falling on a post-stroke patient during rehabilitation. Despite that, the solid AFO unnecessarily restricts the push-off, increasing the walking energy cost [3], [4]. Here, the robotics technology improves the AFO by including actuators on the articulated joints to control the walking gait. As a result, the improved AFO can still have the locking feature without unnecessary foot off restriction at the same time.

Usually, doctors or therapists prescribe the AFO for patients with gait impairment. In this work, the design and prescription of AFO are not about suggesting the most cutting edge AFO to the patient. More importantly, is that the AFO should match the patient’s needs in real-time. For instance, a patient with an amputee requires an active powered AFO to generate the walking movement for him. Months upon treatment using the active AFO, the patient is diagnosed with a different AFO that partially supports the walking, so he/she can walk more naturally. This example shows that the AFO prescription is an iterative and individualized process [5]. Fabrication of the AFO should be done without time-consuming factors. Sometimes, it takes time to get the new AFO suitable for the patient’s needs. If the AFO fabrication process takes a long time in an iterative and individualized process, then the fabricated AFO may no longer be appropriate. The AFO design and prescription are also a collaborative process because the patient may need the family’s help, for example, to put on the AFO. The family should have basic knowledge about the prescribed AFO to be attached in the right way to support the patient. Besides, the family also plays the role of financial support for the patient. Sometimes, the real challenge of prescribing an AFO is whether the patient and his/her family can purchase the expensive AFO or not.

![Figure 1. Foot drop illustration: with AFO (solid grey line) and without AFO (black dash line).](image)

Improving the ancillary or support equipment, such as the AFO, optimizes the patient’s benefit when using in gait rehabilitation. The patient gets the most benefit of gait treatment from low cost, easy to fabricate, safe, long term usage, and personalized AFO. Robotic technology can be the means to achieve this. By having an actuator on a personalized AFO, the mechanical properties of an AFO can be changed accordingly to the diagnose. The requirement to fabricate a new AFO can be neglected, making the AFO a long-term rehabilitation program. Because of this, the patient can save their money for buying a new prescribed AFO. However, developing such AFO is challenging, requiring effort and dedication to making the prototype, unlike what we had seen in the science fiction movie.

2. **On-going Research**

In line with personalized AFO for the patient, the Advanced Vehicle research group has developed a passive controllable AFO known as PICAFO. The PICAFO research and development consists of several works, such as the gait detection method, smart MR actuator design, and controller development. In this paper, the details of the works related to developing the PICAFO for personalized gait treatment are presented.

2.1. **Gait Detection based on Biosignal**

The walking pattern, known as gait, is one of the most common forms of human locomotion. The walking gait is a complex, unique, and quasi-periodic phenomenon, where the gait cycle is similar at first glance, but it is not. However, the walking gait can be identified according to each phase consisting of several gait phases. An assistive device such as AFO should control each designated gait phase differently. Therefore, the controller must be able to identify the appropriate timing of each gait phase
with accuracy. Information from the users’ (i.e. EMG [6]–[8], ankle position [9], [10], limb acceleration [11], [12], bending moment [13], and intention [14]) and their interaction with the environment (i.e. Ground Reaction Force (GRF) [15] and foot contact [16]) can be used to identify the gait phase using sensors. Inaccurate gait phase detection means insufficient control. For example, the gait is classified into stance and swing phases. The swing phase requires rotation movement in the plantarflexion movement. Nevertheless, the controller identifies it as a stance phase that requires the dorsiflexion movement. As a result, the controller will generate a dorsiflexion movement instead of plantarflexion. Wrong actions could lead to a fatal injury to the user. Therefore, sensors and gait phase-detection methods must be properly selected to ensure accuracy.

Gait detection by utilizing Tibialis Anterior (TA) and Gastrocnemius Electromyography (EMG) has been experimented with in the AVS research group since 2016. Initially, a fuzzy classifier based on EMG signals for discriminating the walking gait into two phases, such as stance and swing, has been successfully developed [17]. The fuzzy classifier's input and the classification features were the segmented stances and swing EMG signal's statistical properties, such as estimated parameter values of Cauchy distribution. Triangular and Gaussian membership functions were compared in terms of classification accuracy by using different healthy subjects. As a result, the Gaussian membership function performed better than the triangular membership function to detect the walking gait. Even though the triangular membership function is the most common, the Gaussian membership function can be considered in pursuing gait detection. Despite that, the membership function design depends on human factors, which vulnerable to unpredicted error.

Since the features extracted were the signal's statistical property, the signal's stationarity must be confirmed. The stationarity test of EMG signal during isotonic contraction, such as walking, has been conducted in 2017 [18]. The stationarity test methods were reverse arrangement (RA) and a modified reverse arrangement (MRA). The aim was to identify the most suitable window length for sampling the EMG signal in a real-time application, such as gait control using AFO. The result shows differences in the average signal stationarity with window sizes of 100 ms, 500 ms, and 1000 ms. However, 88.57% was obtained when sampling the EMG signal using a window size of 200 ms. The sampling window size, together with the processing time, should be less than 300 ms and a window size of 200 ms is applicable for isotonic EMG signal.

After confirming the window sizes of sampling and processing time-domain EMG features in a real-time application, the classification method was further improved with an artificial neural network (ANN) [19], as shown in Figure 2. The ANN is adaptive to new datasets because of the learning ability compared to the fuzzy method. Similarly, the gait was classified into two focal phases: stance and swing, heel-strike (HS), and toe-off (TO). The developed ANN employs the Levenberg-Marquardt algorithm with five-time input domain features to achieve 87.4% classification accuracy of stance and swing. Figure 3 shows the comparison between the ANN method and the footswitches method, where the latter is considered the golden rule of detecting the gait phase in AFO applications. The result shows that the timing difference in detecting the stance and swing is less than 70 ms, which was acceptable. Thus, it was concluded back then that classifying the gait phases based on EMG using the ANN for AFO controller usage is promising.
Figure 2. Gait classification using EMG signal for AFO controller usage.

Figure 3. Comparison of the ANN method and footswitches in detecting the gait phases [19].

Smart material such as hybrid Magnetorheological Elastomer (MRE) was considered for detecting the gait phase. Graphite (Gr) is introduced as an additive to the hybrid MRE, which enhances the conductivity and rheological properties of the hybrid MRE to be used as force sensors [20], [21]. In principle, the main concept of detecting the gait using the MRE is similar to footswitches, in which detecting the foot contact by attaching it to the foot insole. However, MRE offers flexibility and durability. Firstly, the shape of the MRE can chart the foot contour since it is made of rubber. Secondly, the rubber’s stiffness can be accustomed according to the applied magnetic field; thus, affecting the MRE durability. Thirdly, the resistivity of the MRE is varied due to weight. Therefore, not only detecting foot contact, but the MRE can also be used to measure the Ground Reaction Force (GRF). Figure 4 shows the hybrid MRE sample and its resistance variables given the weight and magnetic field variation, Tesla [21]. It is possible that a smart insole, which is customizable and able to detect the gait phase, can be developed in the future by using this smart material as the foundation.
2.2. Small Scale Magnetorheological Brake for Gait Assistance

Articulated AFO can be controlled actively or passively depending on the actuator. Examples of active actuators are pneumatic [22], DC motor [23], and series elastic actuator (SEA) [10], where they can generate leg movements. On the other hand, several reported passive actuators are springs [24], damper [25], solenoids [26], and magnetorheological (MR) devices (damper [27] or brake [28]) where they maintain the ankle movement in principle. The later mentioned passive actuator, the MR device, is a semi-active actuator because its mechanical properties, such as the braking or damping stiffness, can be proportionally controlled according to the induced current [29].

MR devices utilize magnetorheological fluids to change mechanical properties. When subjected to a magnetic field, the MR fluid solidified in an instant [30]. The solid level depends on the magnetic’s field value, and because of this, the stiffness is controllable. Despite that, the MR fluid tends to sediment when the devices have not been used for a long time. Alternatively, the MR grease solves the sediment problem, but the response is very slow compared to the MR fluid. However, MR grease is not suitable for semi-active walking gait control in real-time implementation. If stiffness is fixed across the gait instead of being controlled, it may be superior to the MR fluid. However, MR brake’s stiffness resulting from MR fluid or grease is still an open issue.

In 2017, the AVS team developed a small scale MR brake intended to control the ankle stiffness of the PICAFO. The drum type MR brake [31], as shown in Figure 5, has a limited size, which was 45 mm diameter and 30 mm thickness because the weight should not exceed 500 grams. If the actuator is bulky, then the PICAFO might become a burden instead of assistance. There is a coil inside the MR brake to provide the serpentine flux. Commercial MR fluid, MRF-132DG by Lord, fills the gap of 0.65 mm between the shaft and the inside wall. As a result, the MR brake can generate 0.26 Nm when induced by 2 A current. The peak braking torque can be improved by decreasing the gap. For instance, when the gap is changed to 0.45 mm, the peak braking torque becomes 0.3 Nm. However, the braking torque is too small for AFO applications. Also, the lesser the gap, the harder the fabrication process.

The drum type MR brake was transformed into a T-shaped MR brake two years later, as shown in Figure 6 [32]. As the name suggests, the shaft shape is like the letter “T,” which increases the active braking surface area. The gap decreased from 0.65 mm to 0.25 mm. Meanwhile, the other parameters, such as dimension and MR fluid type, were maintained under the same constraint. As a result, the peak torque improved by ten times, where 2 A of induced current generates 2.1 Nm stiffness torque. However, the stiffness torque is still considered small compare to other MR devices, such as Naito et al. [33] (5 Nm), Furusho et al. [34] (24 Nm), Kikuchi et al. [12] (10 Nm), and Hassan et al. [27] (11 Nm). The desired performance of the MR brake should be balanced with the available resource and constraints. Thus, developing the small-scale MR devices, which produces high stiffness, is a very challenging task. Although the currently developed MR brake can only partially support the ankle torque due to the low
stiffness torque, the positive effect on the AFO users can be observed by controlling the stiffness accordingly to the detected gait phases.

![Figure 5. Drum type MR brake (a) and braking torque under different radial and annular gaps [31].](image)

![Figure 6. T-shape MR brake (a) and braking torque or damping stiffness concerning induced current [32].](image)

2.3. PICAFO stiffness control development

The controller is an essential part of developing an AFO system besides optimizing the hardware structure based on sensors and actuators selection. Here, a PICAFO controller was developed to control the ankle damping stiffness using MR brake in different gait phases. Initially, in 2016, the PICAFO system employs a fuzzy logic controller (FLC) with two inputs (EMG and ankle position) and one output (voltage to induce current), as shown in Figure 7 [35]. The FLC combining the gait classification based on Gastrocnemius EMG and stiffness control based on ankle position. Figure 5 also shows the MR brake generated 94.41% maximum stiffness during the swing phase and gradually increasing torque from 9.67% to 77.34% maximum stiffness during the stance phase. Foot drop prevention is achieved while at the same time, allowing plantarflexion during the stance phase to shift the bodyweight forward. However, since the FLC was an open-loop control system, the damping stiffness reference amount must be determined through a trial and error process, which was time-consuming.
Alternative control reference, such as ankle velocity in four gait phases: (1) initial contact to foot flat, (2) foot flat to heel off, (3) heel off to toe-off, and (4) swing phase, has been investigated in 2019 [36]. The idea is to generate damping stiffness using the MR brake whenever the ankle velocity exceeds the reference (assist-as-needed). The investigation result shows that the ankle velocity has a proportional relationship with walking speed and body mass index; hence, it can be estimated based on this common information. Compared to previous studies by Kikuchi et al. [11], where only walking speed is considered as an estimator, the inclusion of body mass index improves the estimation while also realizes a personalized PICAFO controlled stiffness. Figure 8 (a) shows the PID controller of PICAFO calculates the appropriate stiffness based on the error and activation condition. As a result, PICAFO with ankle velocity reference can help achieve positive ankle kinematics and muscle activity. As shown in Figure 8 (b), both the normal and overweight subjects' TA and Gastrocnemius muscle activity reduces when they walked using PICAFO with controlled stiffness. If the fixed stiffness is used in normal subjects, then trial and error must confirm that the medium stiffness is the appropriate stiffness. Meanwhile, the controlled stiffness resulted in positive assistance, superior to high stiffness, and slightly inferior to medium and low stiffness. However, the reference's determination does not require trial and error since the ankle velocity reference can be estimated straightforwardly.

3. Conclusion
A Passive Controllable AFO (PICAFO) system, including several research works, such as gait detection method, small scale actuator design, and controller development, was developed to achieve personalized gait treatment goals. While ensuring the light and compact hardware structure by selecting proper
sensors and actuators is important, the controller also proves to be essential. The latest version of the PICAFO system utilizes MR brake to control the walking gait based on ankle velocity reference. The user's common information, such as walking speed and body mass index, is the estimator for estimating the ankle velocity reference. When using the PICAFO with ankle velocity reference, the subjects' muscle activity reduces due to MR brake generates damping stiffness only when necessary. Because of this, a personalized gait treatment using the PICAFO system is possible.

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