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Fuzzy Logic Controller for Current Induced Ankle Foot Orthoses based on Electromyography Biosignal and Ankle Angle

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Abstract – *Ankle Foot Orthoses is a supportive equipment attached to the lower part of the leg to support patient's walking posture, gait. It has been developed for several years using many kinds of actuator that can be controlled electronically. In this paper, a controller development for Passive Control Ankle Foot Orthoses is presented. A Fuzzy Logic Controller is proposed to control the system due to its ability to model human decision process. The proposed inputs to control system are the EMG biosignal for state identification and the angle for torque identification. The controller is expected to produce sufficient current for Magnetorheological(MR) brake to change its stiffness in order to support patient's gait.*

Keywords: Orthoses, Passive Control, EMG biosignal, Fuzzy Logic Controller

1.0 INTRODUCTION

Walking is important activity in human life as it is the simplest way for humans to move their body, symbolizes human mobility [1]. Walking has strong influence on several aspects in human healths. Hence, it is important for post stroke patient to regain back their walking posture, gait through rehabilitation.

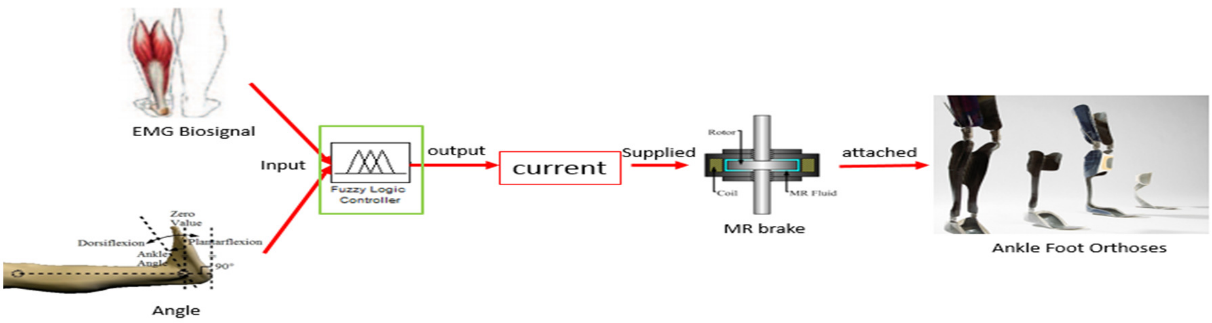

Figure 1: Overview of this study

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In post stroke rehabilitation, the patients use a supportive device such as orthoses to help their training. Orthoses is a supporting device that attaches to surface of human body. Ankle Foot Orthoses, AFO is orthoses that attached to lower leg part as shown in Figure 1, which used to support human's gait.

In the development of AFO, an electronic actuator has taken their part, creating room for control system to improve the whole system. The control system for AFO should deal with a possible lack of coordination between the user and the orthoses (unwanted muscle reaction, reflect). There are two types of AFO's control systems: active control system and passive control system.

The differences between active control and passive control can be seen from the actuator. Active control system usually uses actuator that can actuates movement like motor and pneumatic valve. On the other way, actuators that restrict movement such as damper, brake, or spring are used in passive control system. As reported in [2], there are a lot of developments in active control system, but not for passive control system.

In this study, we develop AFO using the MR brake as the passive element. The MR brake can change its brake degree, stiffness due to applied current. Figure 1 shows the big picture of this study. An EMG biosignal and angle is proposed as the input for control system. EMG will determine the gait state, while the angle will identify torque needed. It will be processed by Fuzzy Logic Controller (FLC), the main focus in this paper shown in green box in order to produce sufficient current which will be applied to the MR brake.

2.0 LITERATURE REVIEW

2.1. Intelligent Ankle Foot Orthoses (I-AFO)

In this study, we adopt the I-AFO introduced by Kikuchi et al. [3] – [6] as an example. It is the only passive controlled AFO as reported in [2].

The devices use Compact Magnetorheological Fluid Brake (CMRFB) to generate torque in order to hold the gait. I-AFO has linkage mechanisms to amplify the torque generated by CMRFB. There is also spring unit to push the foot during plantar flexion. Figure 2 shows the picture of I-AFO.

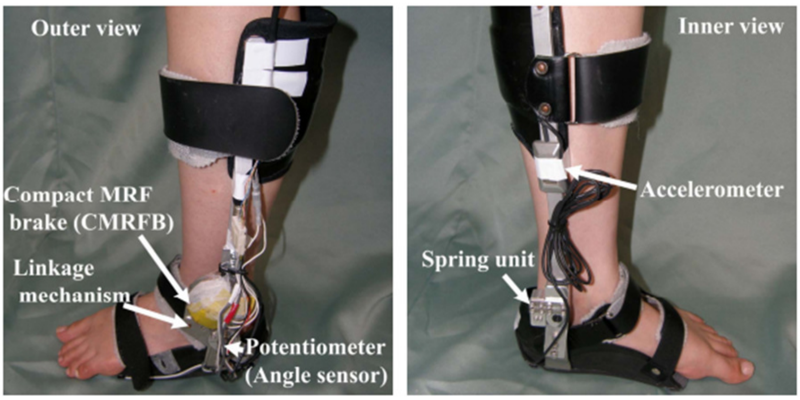

Figure 2: Intelligent Ankle Foot Orthoses, I-AFO [3]

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The device is controlled based on human gait. Figure 3 shows the I-AFO gait classification which classified into three states and they are:

- State 1 from Initial Contact (IC) to the Foot Flat (FF)
- State 2 from FF to Heel Off (HO)
- State 3 from HO to IC

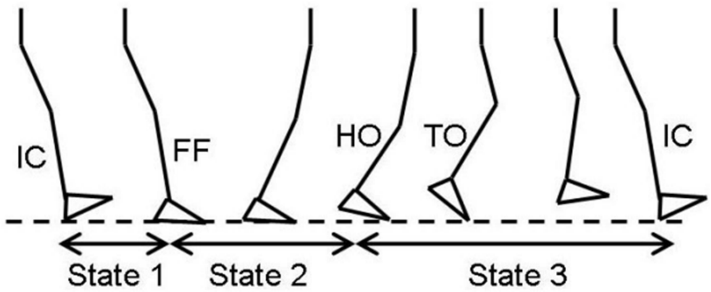

Figure 3: I-AFO Gait Classification [3]

I-AFO is controlled using Finite State Machine (FSM) method. The CMRFB stiffness will be different for each state and the process will move from one state to another state after certain condition or judgment is met.To detect the gait accelerometer and potentiometer is attached to the I-AFO. The accelerometer is used to identify the start of state 1 as they observe rapid changes of acceleration at IC. In this study, the accelerometer is replaced with a muscle sensor to read the muscle activity as the muscle activity can be used to classify the gait [7] into two states. It will be shown in section 3.

2.3. EMG Application

Electromyography or an EMG biosignal is signal produced by muscle activity measured in voltage unit and range from 100 μV to 10 mV peak to peak. Usually the data recorded at a sampling rate 1000 Hz [8]. EMG provides us information to detect phases of human gait [7]. Because of that, EMG can be used to imply people's movement action 30 – 100 ms in advance [9] lead to widely used of EMG biosignal in clinical diagnosis, rehabilitation, and prosthetic orthotic control.

Although there is a problem in time lag and noise, EMG can provide an intuitive interface and be used for every patients who are not paralyzed [10]. Even if the muscle is not strong enough, the signal of intended motion can still be recorded. Several studies have considered using both EMG sensors and mechanical sensors for locomotion mode recognition. It does prove that the EMG added considerable information rather than adding another mechanical sensor [11].

A proportional myoelectric control as proposed in [12] showed a pneumatic muscle controlled by a surface EMG of soleus muscles. Another work in [13] also highlighted how the EMG is used to predict intended motions for active control orthoses. The previous works showed that the EMG biosignal can be used in controlling ankle foot orthoses.

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2.4. Fuzzy Logic Controller (FLC)

In recent years, the use of FLC becomes popular due to its ability being able to model human decision making process [14]. The theory behind FLC is to represent precision value into significant value and it has proven to be successful in many applications.

The most common FLC application is a traffic light control. Mario et al. in his work showed how 4 traffic lights are controlled using FLC which constructed in parallel resulted in better performance, fault tolerance, and specific phase management [15].

In biomechatronics application, FLC has been used to control finger force on prosthetic hand [16]. The controller objective is to move finger joints angles representing grasping motion which the initiation is evaluated via a surface EMG measured from the fore arm of the user. The results showed the FLC has good performance to follow the reference trajectory closely.

In this study, the FLC is proposed to control the current induced ankle foot orthoses using EMG and angle as the input. As the input behavior is not periodic, but quasi periodic, FLC is a good choice with this kind of input signal rather than a classic PID controller.

3.0 METHODOLOGY

In this paper, the focus is on designing the FLC to produce sufficient current for the MR brake. Firstly, the controller purposes are defined. Secondly, a torque definition and gait classification are defined based on the inputs. Finally, the FLC is defined with reffering back to our gait classification.

3.1. Controller Purpose

Post stroke patients might have gait impairment which is drop foot [17]. It is a condition where the foot has inappropriate dorsiflexion during swing phase lead to toe contact at beginning of the stance phase (supposed to be heel contact first). Figure 4 shows a scenario of the drop foot.

Figure 4: Drop Foot

Therefore, the controller purpose is to prevent the drop foot with details at:

- the stance phase, the device should advance smooth gait transition.

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- the swing phase, the device should lock the foot in such a way the toe is higher than the heel, so the heel will contact the ground first.

Based on that, the device should generate high enough torque at the swing phase to lock the foot, but low to moderate torque at the stance phase.

3.2. Torque Identification and Gait Classification

Data collection of ankle's angle and EMG biosignal from walking activity of healthy people has been done to identify the torque and to classify the gait. The sensor is connected to data acquisition (DAQ) which is integrated with LabVIEW. Then, the data were recorded using read measurement function in LabVIEW.

The angle is recorded using a quadrature rotary encoder with a resolution of 500 pulse per revolution (ppr) attached to the right ankle. The measurement is taken from three steps walking, and zero-degree angle is assumed as the angle resulted from standing. When the ankle rotates forward, it becomes positive, and vice versa.

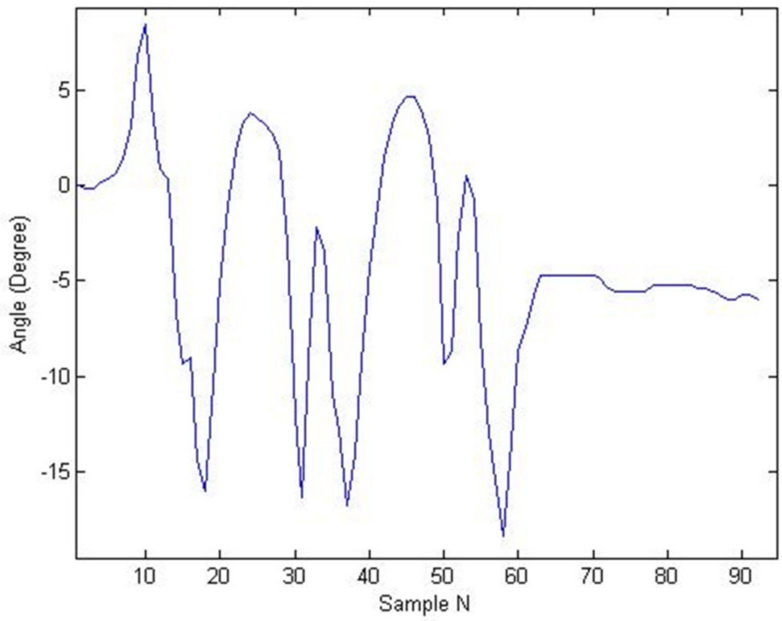

Figure 5: Ankle Angle Walking

From Figure 5, the maximum value for ankle angle captured is more positive 5 degree and the minimum value is less negative 15 degree. A simple modelling is done to determine the torque needed for a certain degree. The foot is assumed to be homogeny and the center of mass is taken to calculate torque resulted from it. Figure 6 shows how the torque is defined. W is the weight of the foot center of mass.

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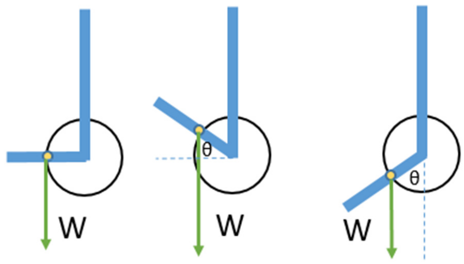

Figure 6: Foot Torque Definition

For maximum angle, the torque calculated is 0.996τ and for minimum angle is 0.2588τ, where τ is the foot torque at zero degree. It can be concluded that the torque to support the ankle is gradually increasing from minimum angle to maximum angle.

On the other hand, the EMG biosignal is recorded using a muscle sensor. The output of the sensor is not a raw EMG, but amplified, rectified, and smoothed signal which works well with microcontroller. The signal is amplified again in the LabVIEW for signal overlapping purpose. Figure 7 shows the EMG biosignal recorded for walking activity of healthy people. The signal is measured by placing the electrode at gastrocnemius muscle following the recommendations and procedures by SENIAM [18].

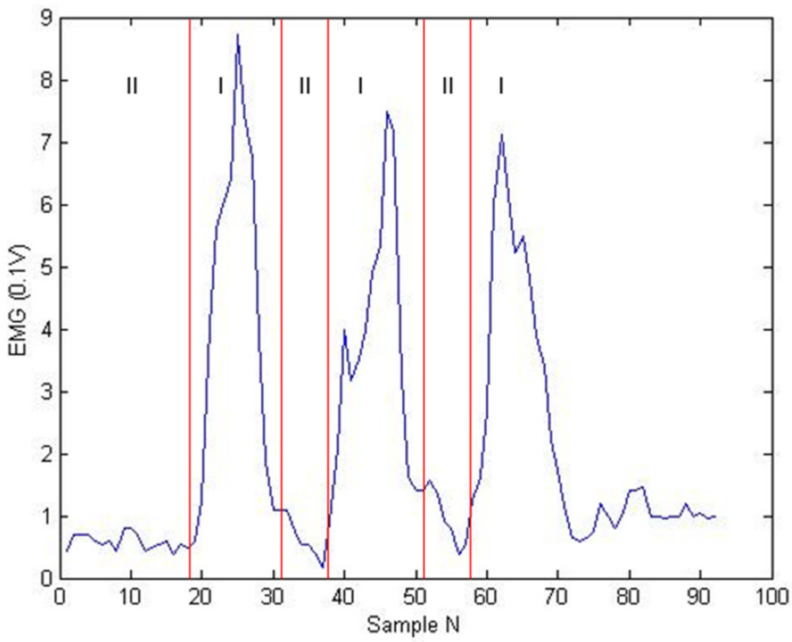

Figure 7: Recorded EMG biosignal of Walking

As shown in Figure 7, it is found that when touching the ground or stance phase, the value of EMG suddenly goes up meaning the corresponding muscle is in contraction, but it stays near the lowest

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value during the swing phase. The EMG biosignal then is defined into two types: I is when the foot touches the ground, and II is when the foot is swinging.

Based on this, the gait is classified into two states:

1. Stance phase (I), when the foot touches the ground, from IC until HO.
2. Swing phase (II), when the foot does not touch the ground, from TO until IC.

Figure 8 shows the proposed and simplified gait classifications for our controller design.

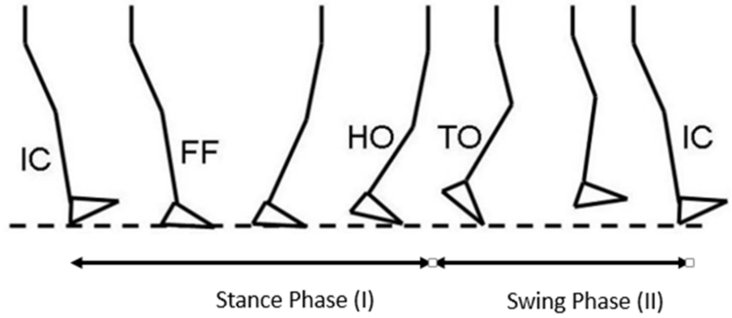


Figure 8: Proposed Gait Classification

Then the signal is overlapped to identify the relation between angle and EMG. As shown in Figure 9, at the start of stance phase (I), the angle is at a minimum position then increased gradually until the top, and it goes down again to start the swing phase (II).

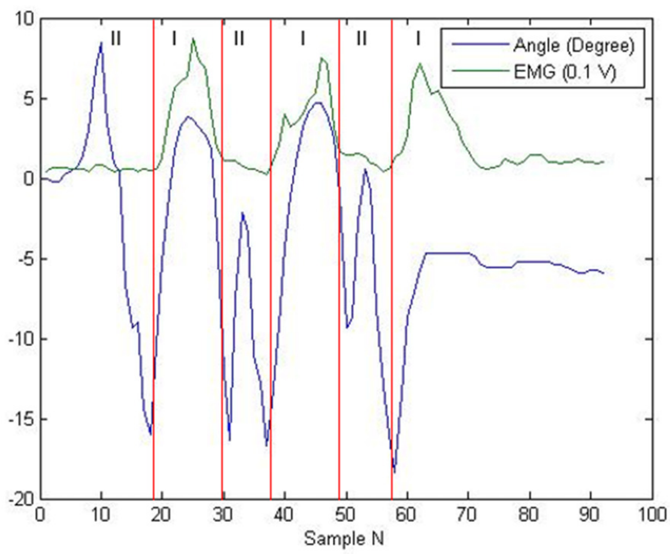
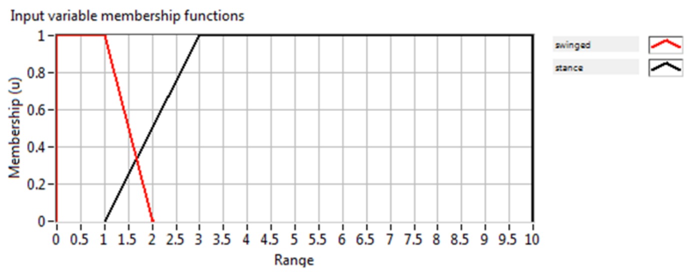


Figure 9: Angle and EMG relation

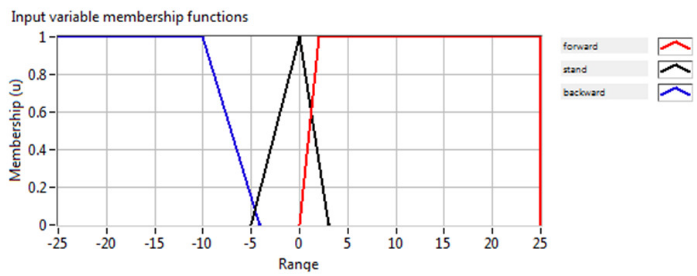
At the swing phase, it is observed that the angle does not stay at the same value indicates that the locking feature by the ankle foot orthoses is needed. By locking the foot during the swing phase, the angle can be expected to stay in a positive value before the initial contact, prevent the drop foot.

3.3. Fuzzy-based Controller Design

In this study, the Ampere current and torque have a proportional relationship. As smooth gait transition at stance phase is wanted, the AFO controller should generate Amperes that gradually increase from low to high as referred to the previous conclusion that the torque is gradually increasing from a minimum angle to maximum angle. For the swing phase, the device is wanted to lock the foot at a forward degree so the controller should generate a high current for locking mechanism. Then a set of membership functions is defined for the inputs and output as depicted in Figure 10.



(a)



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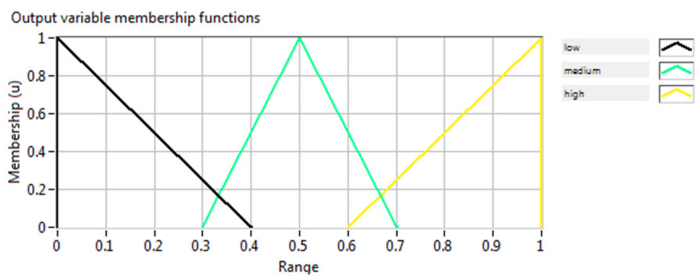

(c)

Figure 10: Membership functions of (a)EMG, (b)Angle and (c)Current

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EMG is classified into stance and swing to identify the gait state while Angle is classified into forward, stand, and backward. The output current value is classified into low, medium, and high with assumption that the current value is proportional to the torque value.

In this paper, the control system differentiates each membership functions for a certain range. Table 1 shows the range for each input and output membership functions. The membership function is chosen to be trapezoid-like because it is suitable for system that using interval range. It is easy to determine the necessary parameters for trapezoid membership function, which is good for preliminary stage of control system development [19].

Table 1: Membership Function Range

Variable	Membership Function	Range
Angle (θ^o)	Forward	0 to 25
	Stand	-5 to 3
	Backward	-4 to -25
EMG (mV)	Stance	1 to 10
	Swing	0 to 2
Current (A)	Low	0 to 0.4
	Medium	0.3 to 0.7
	High	0.6 to 1

After the membership functions were defined, the rules applied to the system were next to be defined. The rules involve all possible combinations of input, but have extra two rules to emphasize the different between stance phase and swing phase. The following two extra rules are:

- If EMG is Stance, then Current is Low
- If EMG is Swinged, then Current is High

Note that the current is high at the swing phase only at forward angle in order to prevent the drop foot. On the other hand, the current is gradually increased at the stance phase. Table 2 shows the rest of the rules.

The total rules are eight, the consequent implication method used is an AND (minimum) method and a defuzzification method used to get the output is the Center of Area (CoA) method. The relationship between inputs and output in the form of surface is shown in Figure 11. It is observed that a portion where the maximum value of current is staying around 0.5 when EMG is stance.

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Table 2: Output Current

		Angle		
		Forward	Stand	Backward
EMG	Stance	High	Medium	Low
	Swing	High	Low	Low

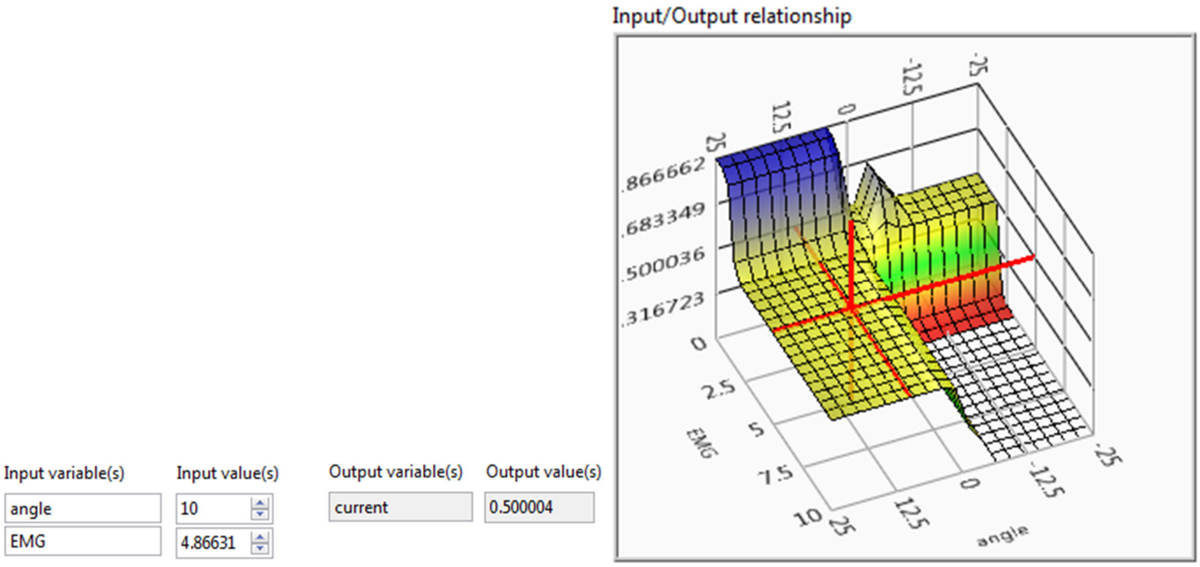

Figure 11: Output Current During State I (Stance)

Meanwhile, when EMG is swinged, for the same value of angle of 10 degree, the current will be high at 0.8662 A as shown in Figure 12. The significant different between the stance phase and swinged phase in the surface fuzzy is the results of the two extra rules added to the system to emphasize the differences.

4.0 RESULT AND DISCUSSION

The controller was simulated by using the previous angle and EMG signal data. The simulation was done using LabVIEW and everything was set according to our previous consideration. Figure 13 shows the inputs and output of the controller.

The current behaves as desired. It is on the low region when the muscle contracts, and oppositely on the high region when the muscle does not contract. At the end part of walking, the current stays at the low region because the subject was stopped walking shows that the system can recognize when the subject is stand or walking.

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However, in this simulation, the system failed to reach a high region. It just barely stays around 0.5 A where it is supposed to reach above 0.6 A. The change of membership functions are needed to improve the controller behaviour, also additional of membership functions to make the functional system more precise.

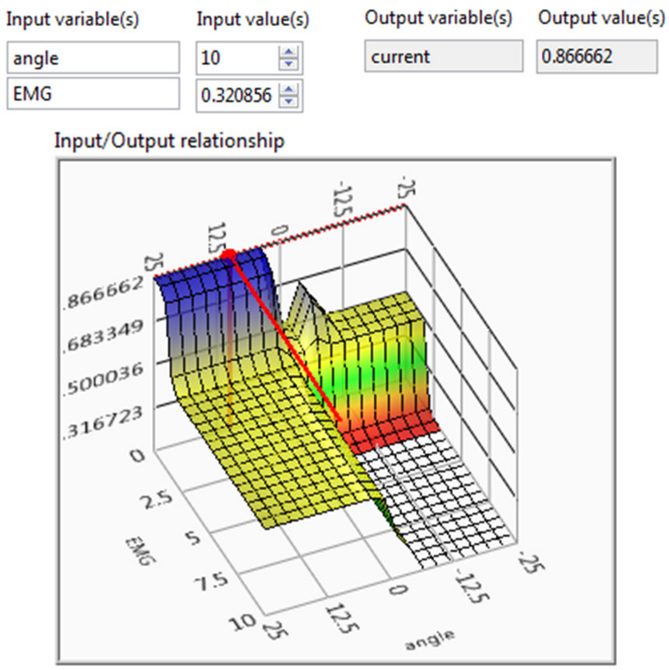

Figure 12: Output Current During State II (Swinged)

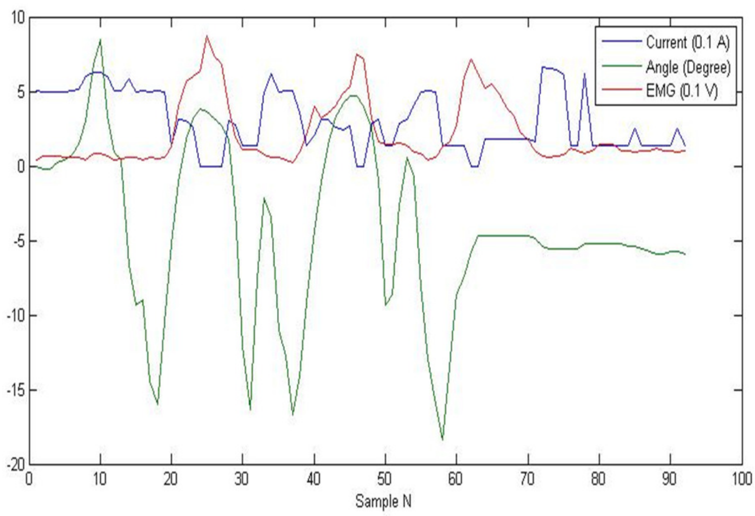

Figure 13: Current, Angle, EMG

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5.0 CONCLUSION

In this paper, a preliminary work on the development of controller for AFO is presented. FLC is used to generate Ampere which will be applied to the MR brake based on the input's value, EMG and angle. The purpose of control system was defined as to prevent the drop foot. In addition, the gait classification was defined based on the observation of angle and EMG signal during walking which was recorded using LabVIEW. The rules for the FLC are constructed according to the gait classification and the FLC is expected to generate gradually increasing current at the stance phase and a high current at the swing phase for forward angle. Simulation has been done in LabVIEW and the behavior of the current during walking activity was observed. Improvement on the FLC is needed, either changing the parameters or even adding the membership functions due to the system failure to reach a high region of current.

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