Jurnal Teknologi

Full Paper

FUZZY LOGIC CONTROL FOR ANKLE FOOT ORTHOSES EQUIPPED WITH MAGNETORHEOLOGICAL BRAKE

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Article history
Received
21 March 2016
Received in revised form
5 June 2016
Accepted
18 October 2016

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Graphical abstract

Abstract

This study focused on the development of passive control ankle foot orthosis (PICAFO) for a specific purpose such as preventing foot drop in the post-stroke patient. The PICAFO utilized the magnetorheological (MR) brake as the actuator in which the braking torque was controlled by regulating direct current (DC) from current driver. The Fuzzy Logic Controller (FLC) was employed to control output voltage for current driver based on the inputs, i.e. Electromyography (EMG) bio signal and ankle position. Walking experiment to test the controller was carried out on a single subject where the input and output FLC was monitored and logged. The results showed that the output voltage of the FLC was 94.41% of the maximum output (high) on forward ankle position during swing phase and gradually increase from 9.667% to 77.34% of maximum output during stance phase. The FLC successfully controlled the output voltage according to the required needs. According to the experimental results, the FLC strategy was applicable for PICAFO realizing it contributes to prevention of foot drop.

Keywords: Ankle foot orthosis, foot drop, passive control, walking gait, electromyography bio signal, fuzzy logic controller, walking experiment

Abstrak

Kajian ini memberi tumpuan kepada pembangunan kawalan pasif orthoses buku lali kaki (PICAFO) bertujuan untuk tertentu seperti mengelakan kaki jatuh bagi pesakit selepas strok. Magnetorheological brek (MR) digunakan sebagai penggerak untuk PICAFO di mana kilas pembrekan dikawal dengan mengawal arus terus (DC) daripada pemacu arus. Pengawal Logik Kabur (FLC) digunakan untuk mengawal voltan yang dikeluarkan oleh pemacu arus berdasarkan isyarat bio Electromyography (EMG) dan kedudukan buku lali. Eksperimen berjalan untuk menguji pengawal telah dijalankan pada subjek tunggal di mana masukan dan keluaran FLC dipantau dan direkodkan. Hasil menunjukkan bahawa voltan keluaran daripada FLC adalah 94.41% daripada keluaran tertinggi pada kedudukan buku lali ke hadapan semasa fasa ayunan dan meningkat secara beransur-ansur daripada 9.667% kepada 77.34% daripada keluaran tertinggi semasa fasa pendirian semasa fasa pendirian. FLC Berjaya mengawal voltan keluaran mengikut keperluan. Maka strategi FLC dapat membuat PICAFO menyedari pengelakan kaki jatuh.

Kata kunci: Orthoses buku lali, kaki jatuh, kawalan pasif, kiprah berjalan, isyarat bio electromyography, pengawal logic kabur, eksperimen berjalan.

1.0 INTRODUCTION

In Malaysia, there were more than 50.000 stroke cases reported annually. Stroke placed third in rank as a major cause of death after heart diseases and cancer. Not all of the stroke cases lead to death; there are also reported survivors suffering from long-term disabilities. According to the National Stroke Association, 25% of stroke survivors recover with minor impairments foot drop. Foot drop is a condition when the foot suffers from dysfunctional dorsiflexion movement and uncontrolled plantarflexion movement which affects the walking posture or gait of an individual. During swing phase, the foot cannot be cleared from the ground which leads the patient to do an exaggerated flexion of the hip and knee. Then, at the start of stance phase, the heel will strike the ground first causing the foot to do plantarflexion movement absorbing the shock. If uncontrolled, it causes the foot to slap the ground and the risk of stumbling is high. It was necessary for the post-stroke patient to regain their walking ability and it can be done through rehabilitation [1].

In post-stroke rehabilitation, a patient uses an ancillary device such as orthosis to help them during the physical training. Orthosis is a supporting device attached to the human body surface and, to be more precise, Ankle Foot Orthosis (AFO), as the name suggests, is an orthosis placed on lower part of the human leg to support the ankle. In the development of AFO, electronic actuators such as motor and pneumatic have their parts in creating room for the control system to improve AFO. In particular, there are two types of control systems: active control and passive control. The active control system generates the leg movement by using actuators such as a motor or pneumatic, whereas passive control system restricts the ankle movement by using actuators such as damper or brake [2].

Active control systems for orthosis is an actively researched field, while passive control systems still lacks research publications, as reported by Jiménez-Fabián *et al*., [2]. Most of the orthosis were developed to control ground-level walking by utilizing mechanical signals such as position, velocity, and accelerometer to detect the gait for purposes of control. Ground level walking translates to normal walking on flat ground without any disturbance such as stairs or hills. A gait pattern generator was presented in [3] where the trajectory of the foot was tracked to follow a reference value that was generated by the controller. Another work showed a finite state machine method for gait control where the gait was divided into several states and controlled differently in each state. There are conditions that have to be met in order to move from one state to another state. For example, the variable impedance on stance state and PD position control on swing state [4]. Variable impedance controls the motor velocity by changing the impedance based on the situation. Hence, they are active control measures.

The signal measured was not only mechanical signals. EMG bio signal can also be use as the measured signal. EMG bio signal is a signal which measures from surface muscle activity, and it is measured in mV. Proportional EMG control is presented in [5] where a pneumatic muscle is controlled based on the amplitude of the measured EMG signal. Another work showed that EMG signal was measured and converted into force or torques [6]. Later, it was used to control the leg kinematic. Previous works have shown that the active control system is an active research field compare to the passive control system. However, weight saving is a constant challenge in developing an actively controlled AFO because the original leg is still available unlike prosthesis where the device replaces the missing limb. Passive controlled AFO has been suggested as an alternative to design AFO. In particular, for preventing foot drop, compared to active control, the passive control scheme has considerable advantages regarding cost, size, safety, and weight [7] [8]. Intelligent Ankle Foot Orthosis (I-AFO) introduced by *Kikuchi et al*., 2010 [8 - 10] is the only passive controlled AFO in existence as reported by Jiménez-Fabián *et al*., [2].

I-AFO has been developed for several years. It utilizes magnetorheological brake (MR brake) as the semi-active element, but it is still controlled passively. I-AFO is controlled by classifying the gait before applying the velocity control on each state. The gait was classified based on the mechanical signal. In earlier years, foot switch was used to classify the gait into four states. The foot switches were placed on the toe and the heel. They gave a digital input of 00, 01, 10, and 11 so the gait can be classified into four states [9]. During the next development, the sensors were changed to accelerometer and potentiometer due to the durability of the foot switch sensor [8]. The gait classification has also been simplified into three states by changing the sensor [9]. However, the control algorithm to decide the recent state was harder than before. In order to change from one state to another state, the foot condition must exceed a threshold value of acceleration and position set by the controller, and it was different for each individual [10]. The need for an expert during training to set the threshold value remained inevitable. In consideration of the above matter, a control model was developed to discard the need for an expert to be present to determine the threshold value [10].

In this study, a passively controlled ankle foot orthosis was developed. Hence why it is named as PICAFO (passive control ankle foot orthosis). Similar to I-AFO, PICAFO also utilizes MR brake as the actuator. However, PICAFO is controlled based on the electromyography (EMG) bio signal and ankle position. By using EMG bio signal, the gait classification can then be simplified into two states. Moreover, regarding inactive value, the EMG bio signal has similarity from one person to another which foregoes the need to change the parameter for each individual. Since walking is a quasi-periodic activity and no mathematical model is available for it [11], fuzzy based controller was chosen to be the PICAFO controller because of its capability to model human decision-making process [12]. Regarding classification purposes such as gait classification, FLC was suggested due to its ability to arrive at the answers from just relying on rogue input information in simpler ways [13].

The development of PICAFO is presented in this paper. First in order, PICAFO overview presents the whole process of PICAFO controller which displays the need for gait classification in the aspects of controller-device design. Section 2 shows the gait classification based on EMG signal before designing the fuzzy controller. Following after-wards, the fuzzy membership function and its rules are then built heuristically. Next, a simulation of the fuzzy surface is presented in order to observe the behavior of input-output of the designed controller. The experiment was conducted with a real device to see the performance of the controller's input behavior tracking and presented in section 6. Finally, concluding remarks are presented at the end.

2.0 METHODOLOGY

Figure 1 shows the overview of the PICAFO system. PICAFO consists of the structure, the actuator, the controller, and the measured signals. The structure has two main parts, which are upper and lower part. The upper part is connected to the calf, while, the lower part serves as the footwear. The parts are interconnected with a hinge part that is parallel to the ankle point. The hinge is equipped with the MR brake to replace the function of the feeble ankle. The structures are made of rigid material covered by soft accessories to protect the leg. The MR brake which is attached in parallel with the ankle joint can generate a torque to affect the gait. The torque generated is proportional to the current controlled by the controller.

There is no walking model provided in this study. Therefore, the controller is designed heuristically based on the observation of input behavior. FLC was adopted as the heuristic controller algorithm. It determines the voltage to drive current output based on the inputs: The EMG bio signal and ankle position, which identified the gait. In this study, the gait was classified into two states: stance phase (I) and swing phase (II) with further details on foot positions named Foot Flat (FF), Heel Off (HO), Toes Off (TO), and Initial Contact (IC). The output of the FLC, a voltage, is used to drive the current for the MR brake. The ideas of the controller were, if the position of the ankle is not right, the brake will be turned off to ease the movement. Instead, if the position is correct, the brake will be turned on to hold the position.

In most cases, FLC membership function and rules were defined heuristically [12-15]. Therefore, the observation and understanding of input-output behavior of the controller became critical parts when designing the FLC. A walking experiment has been conducted to observe the EMG bio signal behavior from gastrocnemius muscle during walking. This specific muscle was chosen because it gave a significant contribution and provided a considerable amount of signal during walking. The sensor was attached to the location of gastrocnemius muscle as stated and the subject were told to walk on a moving treadmill in a constant speed. The experiment was recorded using a video camera which was connected directly to a personal computer. On the computer, LabVIEW front panel recorded the measurement on gastrocnemius EMG and the video during the walking activity.

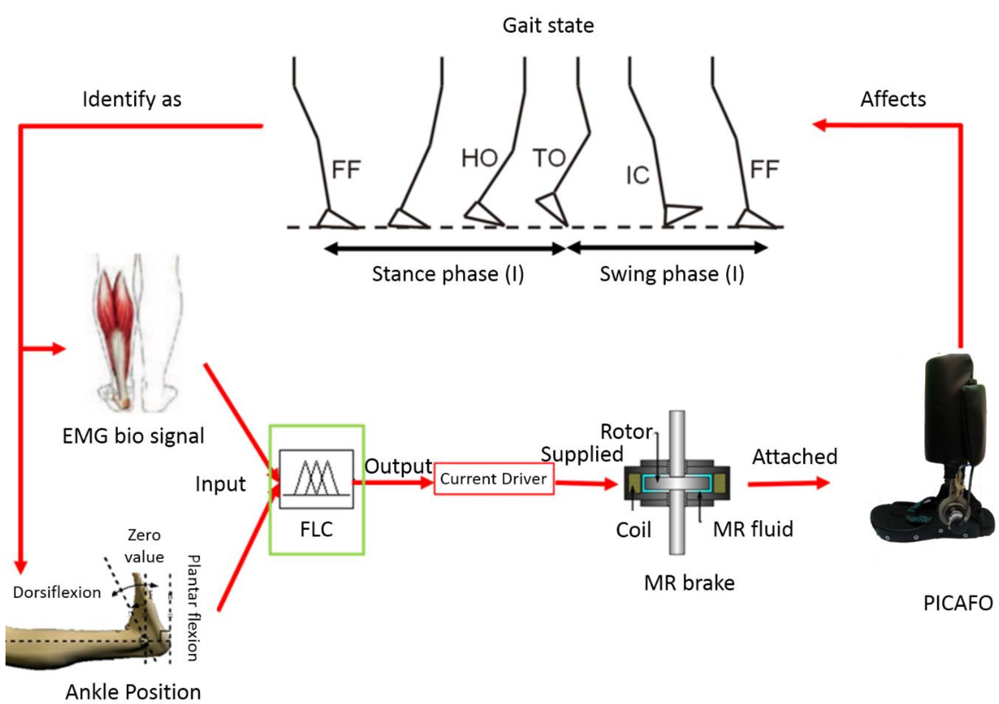


Figure 1 PICAFO system overview

According to the experiment results, it was concluded that the EMG bio signal could differentiate the states, especially the TO and FF. Figure 2 shows the observation of gastrocnemius EMG and video during walking activity on the treadmill.

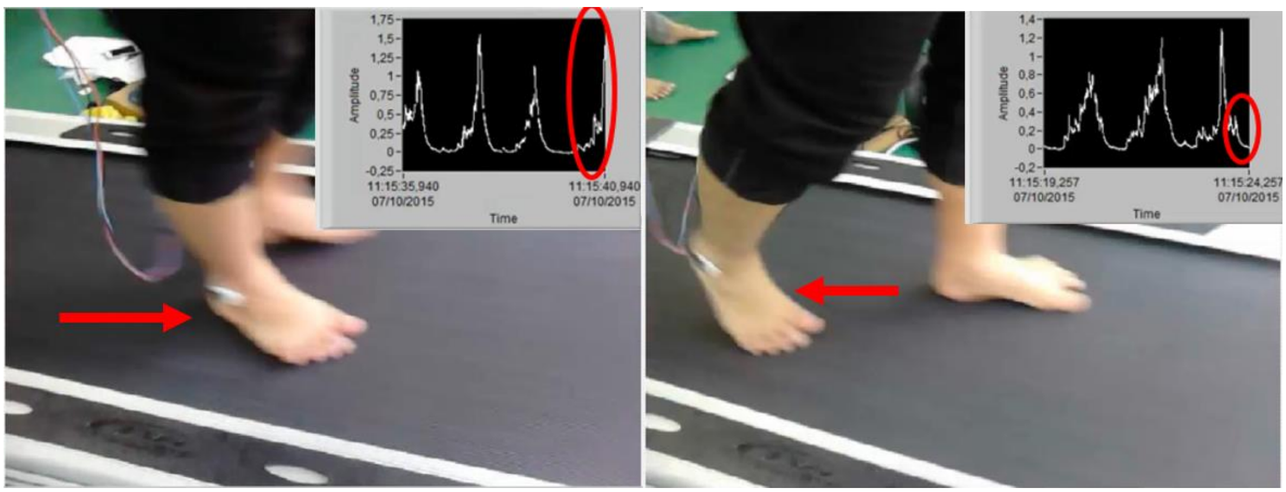
The red arrow is pointing at the recent foot position, and the red circle is highlighting the recent EMG graph. It is clear in Figure 2 that when the foot is fully on the ground (FF), the EMG signal value increases which is a sign of active muscle. On the other hand, when the foot leaves the ground (TO), the signal decreases which represents the inactive muscle. Through this experiment, It is concluded that the gait can be classified into two:

- Stance phase (I): The foot fully touches the ground. From FF to TO the muscle is active.
- Swing phase (II): The foot does not touch the ground. From TO to FF the muscle is inactive.

Figure 3 shows us the gait classification based on EMG bio signal.

The FLC consists of membership function and rules. The number of membership functions and rules should be optimized as much as possible to make a simple yet effective system. In this study, the FLC has five membership functions for the inputs (two membership functions for EMG bio signal and three membership functions for ankle position) and five membership functions for the output voltage. The range of each membership function was chosen heuristically based on the direct experiment. The Gaussian type membership function was opted because this function is smoother than the other membership functions such as triangular or trapezoid.

The EMG bio signal membership functions are labeled as active and inactive as depicted in Figure 4. The range of the membership function is measured from -1 to 10. The active membership function ranges from 1 to 10 with a tolerance of 0.5 while the inactive membership function ranges from -1 to 0.25 with the tolerance of 1.



(a) (b)

Figure 2 EMG signal observation during walking activity. (a) Foot is touching the ground; (b) foot is leaving the ground

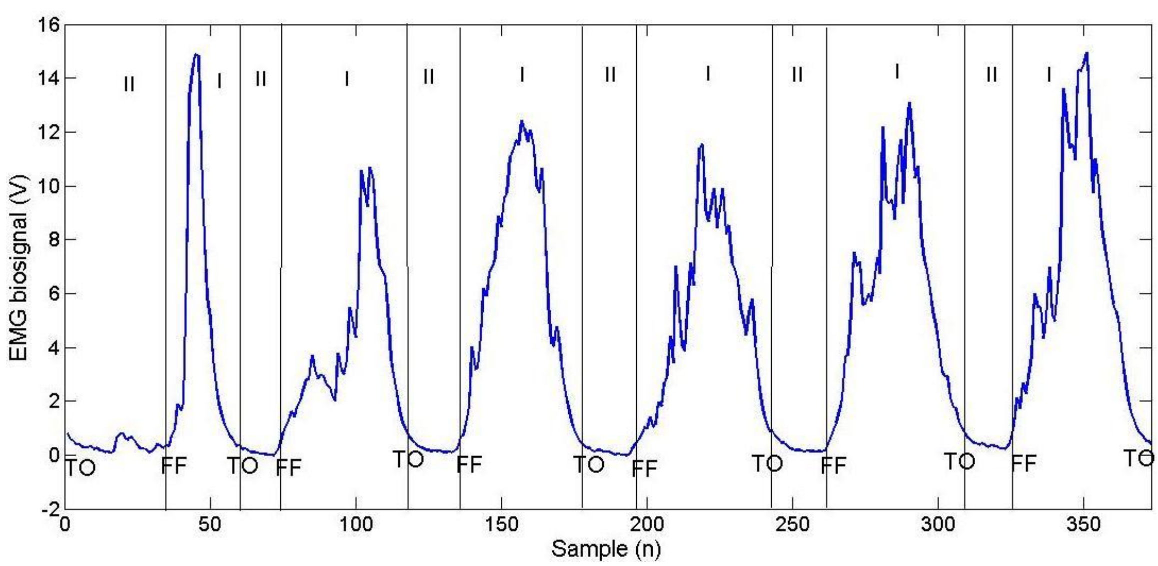


Figure 3 Gait classification based on EMG bio signal. The gait is classified into two: stance phase (I) and swing phase (II)

EMG bio signal membership function starts from -1 to compensate noise caused by the EMG sensor.

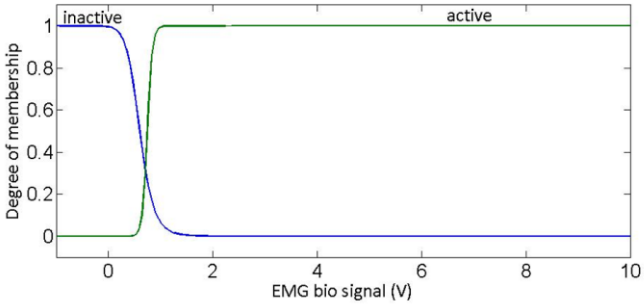


Figure 4 EMG bio signal membership function

The membership functions of ankle position are Backward (**BWD**), Stand (**STD**), and Forward (**FWD**). It ranges from -22.5 to 22.5. **BWD** ranges from -22.5 to -7 with a tolerance of 4. **STD** function ranges from -2 to 0 with a tolerance of 3. **FWD** ranges from 1.5 to 22.5 with tolerance 1.5. The **FWD** membership function starts from a similar position as the **STD** membership function in consideration that the difference between the stand and forward ankle position is small. Figure 5 shows the membership function for ankle position.

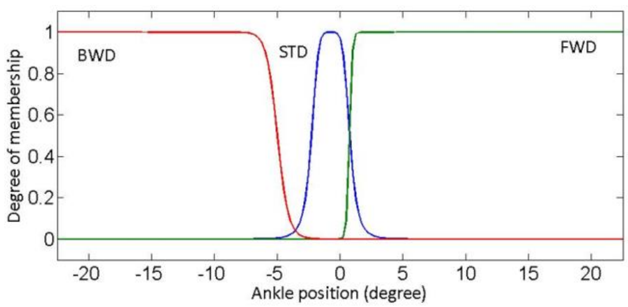


Figure 5 Ankle position membership function

On the other side, the controller output is a voltage driving the current that will be supplied to the MR brake. Each voltage corresponds to a certain current (A) and torque (Nm) value. Table 1 shows the relation between voltage, current, and the torque which is directly proportionate to each other. High voltage corresponds to high current which produces high torque and vice versa [16], [17].

Table 1 Voltage, current, torque relationship

Voltage (V)	Current (A)	Torque (Nm)
4.3	0.3	0.119789
4.4	0.8	0.130126
4.5	1.6	0.224622
4.6	2.58	0.2573001
4.7	3.0	0.271305

The voltage membership function ranges from 4.3 to 4.7 and is divided equally into five membership functions: Low (**L**), Moderate Low (**ML**), Moderate (**M**), Moderate High (**MH**), and High (**H**). Each voltage value as shown in Table 1 becomes the middle point of the membership function. They have a range of 0.05 and tolerance of 0.05. Figure 6 shows the voltage membership functions.

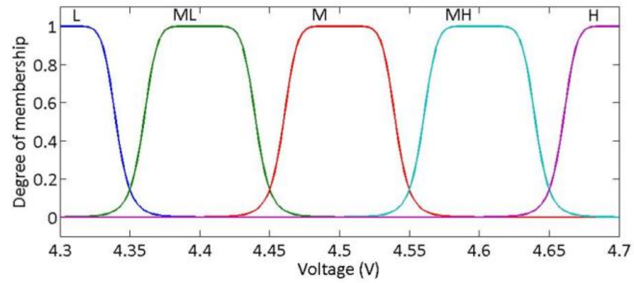


Figure 6 Voltage membership function

The summary of the membership functions is presented in Table 2.

Table 2 FLC membership functions summary

Variable	MF	Range	Tolerance
Ankle Position (°)	Backward	-22.5 to -7	4
	Stand	-2 to 0	3
	Forward	1.5 to 22.5	1.5
EMG biosignal (V)	Active	1 to 10	0.5
	Inactive	-1 to 0.25	1
Voltage (V)	Low	4.3 to 4.325	0.05
	Moderate Low	4.375 to 4.425	0.05
	Moderate	4.475 to 4.525	0.05
	Moderate High	4.575 to 4.625	0.05
	High	4.675 to 4.7	0.05

The rules played important roles in FLC to determine the behavior of controller input-output. In this study, the rules were defined based on the PICAFO purposes which are to prevent foot drop [18], therefore:

- On the stance phase (I), to control the plantar flexion movement which prevents the slap foot, PICAFO should provide torque which is directly proportional to the ankle position.
- On the swing phase (II), to clear the foot off the ground, PICAFO should be able to lock the foot on a forward ankle position. The MR brake should be able to achieve high torque when the ankle position is forward.

The torque is proportional to the supplied current controlled by the voltage. It was concluded that during Stance Phase, the voltage gradually increases. During Swing Phase, the voltage is high for forward ankle position. As mentioned, the inputs have a total of five membership functions which were three and two in each respect. The total rules were the product of the inputs number which is six as summarized in Table 3.

Table 3 FLC rules

Ankle position	EMG bio signal	Output Voltage
BWD	inactive	L
BWD	active	L
STD	inactive	ML
STD	active	M
FWD	inactive	H
FWD	Active	MH

3.0 RESULTS AND DISCUSSION

This simulation is conducted to observe the relationship between the inputs and outputs. A fuzzy system designer in LabVIEW software was used to simulate the behavior of the FLC. After inserting the membership functions and rules design in the fuzzy system designer, the relationship between inputs and outputs were observed in the form of fuzzy surface viewer as depicted in Figure 7. All possible combinations of inputs and outputs were presented in this viewer.

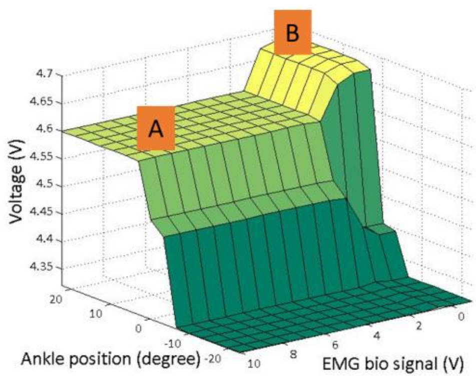


Figure 7 Fuzzy surface viewer of FLC

As seen, when the ankle position is in forward direction, the voltage is high as indicated by measurement A and even higher when the muscle is inactive as indicated by measurement B. It is also observed, the slope differs when the EMG bio signal value is less than 1 and more than one. The differences of voltage behavior between active and inactive muscle could be seen in Figure 8.

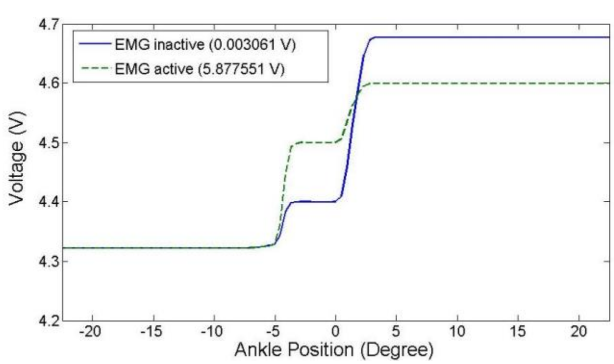


Figure 8 Ankle position vs voltage relationship

The voltage (green dash line) gradually incremented from 4.322 V in between of -22.5° and -5°, to 4.5 V in between of -5° and 0°, and finally to 4.6 V in between of 0° to 22.5° during active EMG. The change was not as significant as the voltage during inactive EMG. The voltage (blue line) increases from 4.322 V in between of -22.5° and -5°, to 4.4 V in between of -5° and 0°. Then, significantly incremented from 4.4 V to 4.678 V in between of 0° to 22.5° during inactive EMG. The output voltage during inactive EMG was lower than active EMG for ankle position below 0° which indicated, during inactive EMG, the foot locking feature of PICAFO was only available during forward ankle position. By locking the foot at forward ankle position, the user can land heel first during the next stance phase indicating the prevention of foot drop [8].

A walking experiment has been conducted to observe the PICAFO controller performance during a walking activity in regards to input behavior tracking. A single male subject participated in the experiment and was instructed to equip the PICAFO prototype on his left leg. In this experiment, the subject walked on the treadmill for two minutes and the data was collected in the second minute of the experiment [19]. With only a single subject, the experiment was repeated several times to get a representative results.

Figure 9 shows the setup of walking experiment. Cytron B106 Rotary encoder was placed on the PICAFO ankle joint to measure the ankle position. An electrode was placed on the surface of the gastrocnemius muscle. The sensing units were connected to the terminal circuit and then onto a personal computer. Inside, the inputs and outputs of the FLC were monitored and logged in using LabVIEW software.

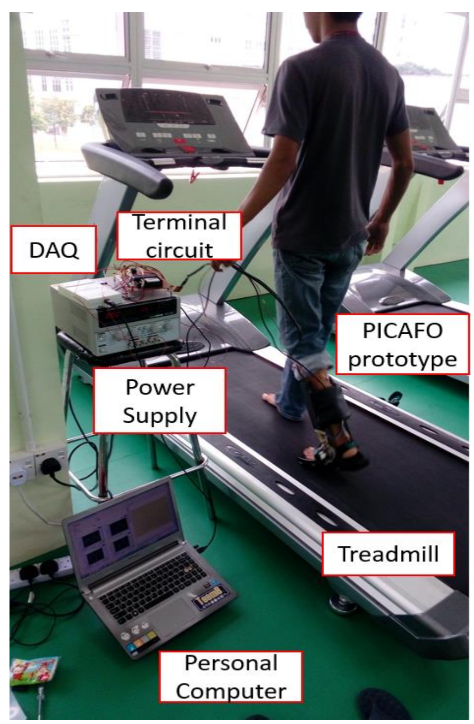


Figure 9 Walking experiment set up

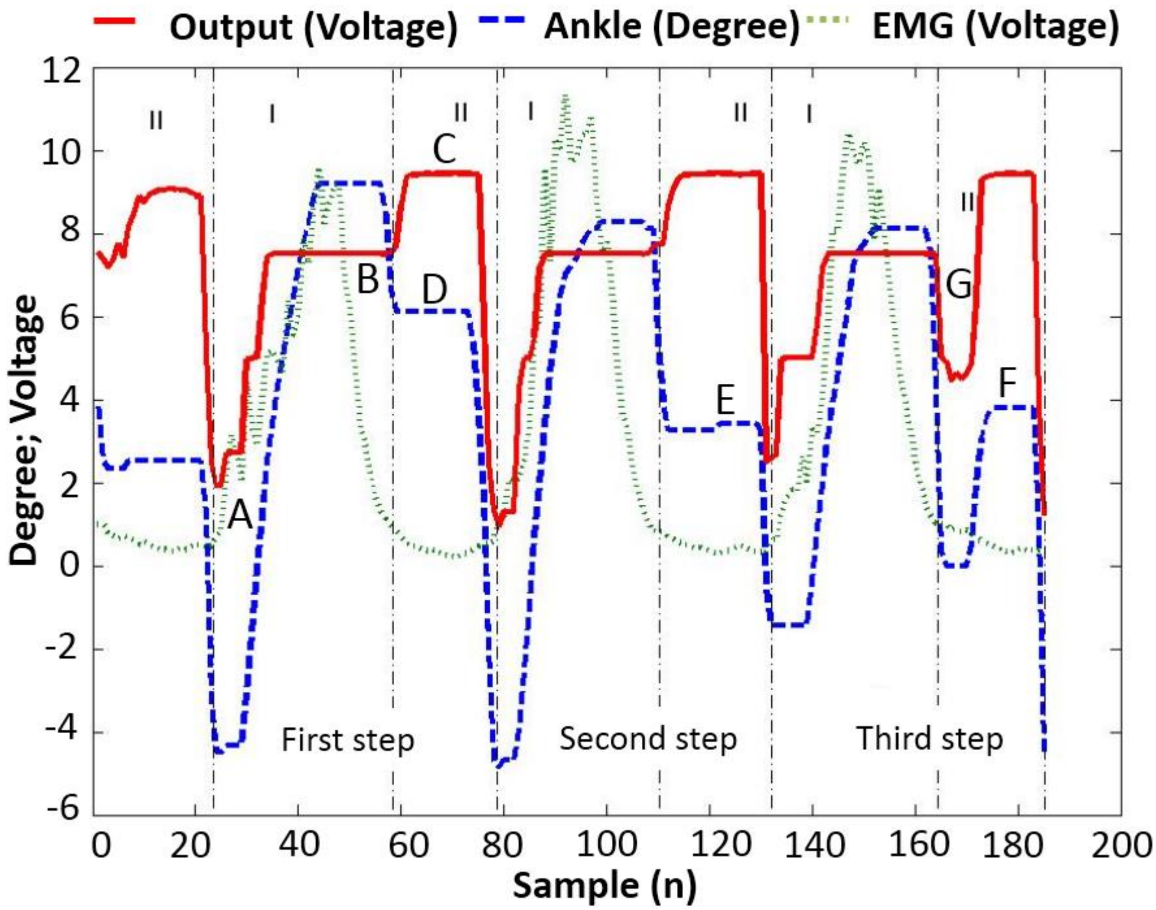


Figure 10 Ankle position, EMG signal, and voltage during walking experiment

A web-cam camera was used to monitor and record the ongoing experiment to ensure the data was correctly registered in. The aforementioned data can be observed inside the LabVIEW program as well.

Figure 10 shows the ankle position, EMG bio signal, and output voltage measured in sample n. The blue dashed line represents the ankle position in degree (°). The green small dashed line, the EMG bio signal in voltage. The red line shows the output voltage in volt unit which was rescaled to 0-10 volt scale for overlapping purposes. I and II indicates the stance phase and swing phase respectively. Lastly, the A –G are explanation labels.

From A to B, the voltage gradually increases from 9.667% to 77.34% of the maximum output (4.7 V) and the ankle position increases until it was being held at around 9° during I. From B to C, the voltage increases during II until it reached 94.41% of the maximum output. Meanwhile, the ankle position dropped to 6° (D) and it was being held for a big portion of the sample during II before it went down which indicates the start of I. The constant positive ankle position during II means the foot was clear of the ground as indicated by D, E, and F explaining foot drop prevention by PICAFO controller.

A different pattern was observed at the third step where the ankle position dropped below zero at the end of I, but it incremented again until it was being held at 4° (F). This pattern explained, the MR brake was not strong enough to hold the foot at the end of I time resulting in negative value of the ankle position at the start of II. However, the controller succeed in allowing the ankle position to increment by lowering the output voltage (G). Factoring in the subject's health, it was normal that the foot could be lifted up. In cases of post-stroke patients, it was hypothesized that if something similar occurred, the foot would stay at negative value meaning the foot drop prevention was unsuccessful.

This results shows that the FLC succeeded in controlling the voltage that drives the current (A) based on the EMG bio signal and the behavior of the ankle position. Also to note, there was an unsuccessful event of foot drop prevention which occurred because the MR brake was not strong enough. The following problem will be addressed as an improvement in future work.

4.0 CONCLUSION

In this study, FLC for PICAFO has been successfully developed heuristically based on EMG bio signal and ankle position. The output of the FLC is the voltage which drives the current that will be supplied to MR brake. The torque produced by the MR brake was directly proportional to the current which is also directly proportional to the output voltage. An experiment was carried out to observe the FLC performance during walking activity. It was observed that the voltage increased from 9.667% to 77.34% of maximum output for backward ankle position (negative) to forward ankle position (positive). It was recorded to be even higher when the EMG was inactive, 94.41% of maximum output. The experiment results agreed with the simulation results where the behavior of the ankle's EMG bio signal, ankle positioning, and the voltage measured were suitable for PICAFO purposes which is to prevent foot drop.

In summary, the FLC succeed in controlling the output voltage behavior for foot drop prevention. To include more, it can also adapt to times when a foot drop prevention failure presents itself as depicted in Figure 10. Further studies to improve the MR brake capability is proposed to improve the PICAFO.

Acknowledgement

The work presented in this study is funded by the Ministry of Education and Universiti Teknologi Malaysia under research university grant VOTE: 09H90.

References

[1] Kikuchi, T., Tanaka, T., Shoji, A., Tanida, S., and Kato, M. 2011. Gait Measurement System To Develop Control Model Of Intelligently Controllable Ankle-Foot Orthosis. *IEEE/SICE International Symposium on System Integration*. 124-129.

[2] Jiménez-Fabián, R., and Verlinden, O. 2012. Review Of Control Algorithms For Robotic Ankle Systems In Lower Limb Orthoses, Prostheses, And Exoskeletons. *Medical Engineering and Physics*. 34(4): 397-408.

[3] Holgate, M. A., Böhler, A. W., and Sugar, T. G. 2008. Control Algorithms For Ankle Robots: A Reflection On The State-Of-The-Art And Presentation Of Two Novel Algorithms. *IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*. 97-102.

[4] Böehler, A. W., Hollander, K. W., Sugar, T. G., and Shin, D. 2008. Design, Implementation And Test Results Of A Robust Control Method For A Powered Ankle Foot Orthosis AFO. *IEEE International Conference on Robotics and Automation*. 2025-30.

[5] Gordon, K. E., Gregory, S. S., and Daniel, P. F. 2006. Mechanical Performance Of Artificial Pneumatic Muscles To Power An Ankle–Foot Orthosis. *Neural Networks.* 39(10): 1832-41.

[6] Fleischer, C., and Hommel, G. 2006. EMG-driven Human Model For Orthosis Control. *Human Interaction with Machines*. 69-76.

[7] Ma, L., Yang, Y., Chen, N., Song, R., and Li, L. 2015. Effect Of Different Terrains On Onset Timing, Duration And Amplitude Of Tibialis Anterior Activation. *Biomedical Signal Processing and Control.* 19: 115-121.

[8] Kikuchi, T., Tanida, S., Otsuki, K., Yasuda, T., and Furusho, J. 2010. Development Of Third Generation Intelligently Controllable Ankle-Foot Orthosis With Compact MR Fluid Brake. *IEEE International Conference on Robotics and Automation.* 2209-2214.

[9] Kikuchi, T., Tanida, S., Otsuki, K., Yasuda, T., and Furusho, J. 2010. A Novel Estimating Method Of The Gait State And Velocity Control In The Initial Stance Phase For The Intelligent Ankle Foot Orthosis With Compact MR Fluid Brake (i-AFO). *Journal of JSEM.* 10: 240-246.

[10] Kikuchi, T., Tanida, S., Yasuda, T., and Fujikawa, T. 2013. Development Of Control Model For Intelligently Controllable Ankle-Foot Orthosis. *Annual International Conference of the IEEE EMBS.* 35: 330-333.

[11] Sanchez-Valdes, D., Alvarez-Alvarez, A., and Trivino, G. 2015. Walking Pattern Classification Using A Granular Linguistic Analysis. *Applied Soft Computing*. 33: 100-113.

[12] Altas, I. H., and Neyens, J. 2006. A Fuzzy Logic Decision Maker And Controller For Reducing Load Frequency Oscillations In Multi-Area Power Systems. *IEEE Power Engineering Society General Meeting*. 1-9.

[13] Lee, C. S., and Gonzalez, R. V. 2008. Fuzzy Logic Versus A PID Controller For Position Control Of A Muscle-Like Actuated Arm. *Journal of Mechanical Science and Technology.* 22(8): 1475-1482.

[14] Potluri, C., Kumar, P., Anugolu, M., Chiu, S., Urfer, A., Schoen, M. P., and Naidu, D. 2010. sEMG Based Fuzzy Control Strategy With ANFIS Path Planning For Prosthetic Hand. *IEEE RAS and EMBS International Conference on Biomedical Robotics and Biomechatronics.* 413-418.

[15] Lee, C. S., & Gonzalez, R. V. 2008. Fuzzy Logic Versus A PID Controller For Position Control Of A Muscle-Like Actuated Arm. *Journal of Mechanical Science and Technology.* 22(8): 1475-1482.

[16] Ubaidillah, N. a., Hudha, K., & Kadir, F. A. A. 2011. Modelling, Characterisation And Force Tracking Control Of A Magnetorheological Damper Under Harmonic Excitation. *International Journal of Modelling, Identification and Control*. 13(1/2): 9.

[17] Ubaidillah, Imaduddin, F., Nizam, M., & Mazlan, S. a. 2015. Response Of A Magnetorheological Brake Under Inertial Loads. *International Journal on Electrical Engineering and Informatics*. 7(2): 308-322.

[18] Adiputra, D. 2015. Development of Controller for Passive Control Ankle Foot Orthoses (PICAFO) Based on Electromyography (EMG) Signal and Angle. *Joint International Conference on Electric Vehicular Technology and Industrial, Mechanical, Electrical and Chemical Engineering (ICEVT & IMECE).* 200-206.

[19] Mahon, C. E., and Lewek, M. D. 2013. Individual Limb Mechanical Analysis Of Gait Following Stroke. *Journal of Biomechanics.* 1538125(6): 984-989.