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Robot ankle foot orthosis with auto flexion mode for foot drop training on post-stroke patient in Indonesia

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Abstract

Robot Ankle Foot Orthosis (AFO) has been proven to assist the gait impairment, such as the foot drop. However, development challenge is still remains, such as the trade-off between complexity, functionality and cost. High functionality resulted in high cost, bulky, and complex device. But affordability and simplicity may decrease functionality. Therefore, this research proposed a robot AFO, which has the necessary function of auto dorsi-plantarflexion so it can keep the affordability and simplicity. The robot AFO consists of structure, electronics part and algorithm. The structure is custom made according to the user's anatomy. A brushless DC (BLDC) motor, Force-Sensing Resistor (FSR) and microcontroller builds the electronic parts. The BLDC motor actuates the flexion, while the FSR detects the gait phase to determine the action. Both are integrated by the microcontroller with the P control algorithm that commands the BLDC motor to generate necessary torque so it rotates in a constant speed. A functionality test has been carried out on the robot AFO, where the robot AFO perform a dorsi-plantarflexion continuously in three conditions, such as no load, 1 Kg load, and foot load. The robot AFO successfully performed a constant velocity rotation in both directions, in all conditions. In the case of 1 Kg load, the maximum angular speed is 0.7 rad/s dorsiflexion and -1.8 rad/s plantarflexion. The torque keeps increasing and decreasing from -0.3 Nm to 4 Nm to keep the angular velocity. The result shows that the robot AFO can perform the necessary function to assist the foot drop training. Functionality test on the gait detection has also been done where it shows that the robot AFO can detect the four gait phases accurately. The robot AFO has been tested and future study should test the robot on a real post-stroke patient to see the effect of the gait control in reality.

1. Introduction

The stroke is a disease, where the blood supply channel to the brain is interrupted, either being blocked (ischemic stroke) [1] or broken (hemorraghic) [2]. Up until now, the stroke remains at the top cause of death and disability in the world with over 12.2 million new strokes each year [3]. There are many causes of stroke, and recently the air pollution due to the carbon emission is often associated with the stroke [4], [5]. Pre-venting the stroke in every person is important. However, treating the survivors are also important because they can be a good narrator that promote the green technology, which reduced the carbon emission. Here, the post-stroke patient usually suffers from the gait impairment, such as the foot drop [6], which need to be treated carefully.

The mentioned gait impairment disturbs the patient's walking. The foot drop makes the ankle unable to do a dorsiflexion during the swing phase, which caused stumbling upon the next initial contact [7]. The training and walking aid are the necessary treatment to enable the patient walks as previously. The training means the patient repeating tons of movement, such as dorsiflexion and plantarflexion to re-learn that movement again. The brain is hoped to find a new blood supply channel to be the substitute of the previously broken or blocked channel. The more the repetition, then the faster is the recovery [2]. On the other hand, the walking aid means any external help that correct the walking gait immediately.

A wearable robot, such as a robot ankle foot orthosis (AFO) can help to provide the necessary treatment for the post-stroke patient with foot drop. Previously, the robot AFO have been developed with various sensor-actuator combination and gait control strategy. A passive ankle velocity control has been demonstrated in a robot AFO equipped with a magnetorheological brake [8], [9]. Robot AFO reported in [10] shows a pneumatically powered soft actuator assisting the walking and standing. Other works as presented by [11], shows the effectiveness of functional electrical stimulation (FES) to improve a motor-driven robot AFO. There are still many kinds of robot AFO that has been developed in the last decade. The development is to aids the disable by improving the gait movement [12] and reducing the walking cost [13]. In the case of Indonesia market, previous research shows that intervention of the robot technology into the orthotic and prosthetic device can help the patient to do self-training [14].

Hardware configuration comparison of the previously developed robot AFO is discussed as follows. The passive AFO with magnetorheological (MR) brake shows similar configuration to active AFO with electric motor actuator. The MR brake or electric motor can be placed directly into the joint [9] or attached to some linkage mechanism first for torque amplification [15]. Of course, placing the MR brake directly is very simple to be done, but the torque achievement is not comparable with the robot AFO that uses linkage mechanism. Study in [9] shows 2 Nm braking torque with direct placement configuration, while study in [15] shows 11 Nm braking torque with linkage configuration. Pneumatic powered AFO can offers high torque achievement (reported to be 23 Nm) [10], however, the compressed air tank is necessary for the movement. The air tank should also be considered as the wearable part if this kind of AFO want to be used to assist daily activity. On the other hand, a FES controlled AFO has the simplest hardware configuration at it comprises of cable and electrode only without hard actuator [11]. But the electrode attachment might require expert intervention rather than self-attaching by the patient themselves. Inaccurate actuation becomes the issue in implementing the FES commercially. In conclusion, the actuators, such as MR brake or electric motor can offer the simplest hardware configuration and easiness to be worn.

The actual commercial robot AFO product is often over specified and costly, which does not suit the post-stroke patient needs and purchasing ability [16]. This research paper reports a development of a robot AFO which is intended for foot drop patient to train their dorsiflexion and plantarflexion independently. A BLDC motor with embedded planetary gear for torque amplification is installed at the ankle joint. Because of that the developed robot AFO has a simple design with the necessary function. The paper is organized as the followings. Section one is the introduction. Section two tells about the robot AFO necessities function. Section three shows the robot AFO development, while section four shows the testing procedure and setup. Finally, the results are discussed and concluded in the chapter five.

2. Robot AFO Necessities Function

The initial stage of robot AFO development is a discussion with an orthopedist to get the necessary function for a patient with foot drop or spasticity. The orthopedist comes from CV. Kenzie Teknopedis, a small medium enterprise, who sells orthotic and prosthetic (O&P) equipment to the patient according to the rehabilitation Doctor's prescription. The orthopedist suggests that there is no further development of O&P products in Indonesia and the robotic could add value to the current existing O&P products in Indonesia. The followings are the necessary function regarding the foot drop treatment.

The foot drop patient needs support for toe clearance [17], which can be done by generating dorsiflexion during the swing phase. This functionality cannot be found in the conventional AFO. As reported in [18], the conventional AFO can only have variable stiffness to give different effect on the user. The foot is still fixed into one position, usually 90 degrees to the shank. This mechanism enables the toe clearance during swing phase, however, also add unnecessary joint stiffness outside the swing phase. Therefore, a robot AFO must have a controllable articulated joint so it can aid as needed. Both the active and passive gait control schemes can be implemented for developing the robot AFO. The active control means generating the limb movement and passive control means maintaining the limb movement [19]. The orthopedist prefers the active control scheme more for the robot AFO because the dorsiflexion can be generated during the swing phase. Also, the patient can use the robot AFO to train their dorsiflexion and plantarflexion outside the walking activity.

As a summary, the robot AFO should have at least 1 Degree-of-Freedom, which is controllable so it can generate dorsiflexion and plantarflexion. Brushless DC (BLDC) motor is a good choice in this case due to the high torque density and relatively small dimension compare to other active actuators, such as pneumatic and soft actuator. The robot AFO also needs to identify the gait phase correctly, so the control action is right. For instance, the robot AFO only generates dorsiflexion during the swing phase. Foot contact based gait phase detection is suggested due to the straightforward implementation and high accuracy compare to other gait phase classification method.

3. Robot AFO Development Methods

3.1 The Structure

The robot AFO structure is made from polypropylene material and is custom designed accordingly to the user's anatomy so it can be used comfortably. The user is a a 56 years old male with foot drop symptom on the right leg due to the previous is-chemic stroke. Detail measurement of the deformity leg shows the necessary length, circumference and diameter to build the structure throughout several steps, such as casting, filling, rectification, moulding, trimlining and finishing. Figure 1 shows the structure, which cover the foot and shank. Four straps are available to keep the leg firm upon usage. There is a brushless DC (BLDC) motor with diameter of 7 cm and thickness of 5 cm on the ankle joint. Two force sensing resistors (FSR) rest at the bottom of the heel and toe to de-tect the foot contact. Finally, a controller box is available at the back of the shank part. As a whole, the structure is weight less than a Kilogram.

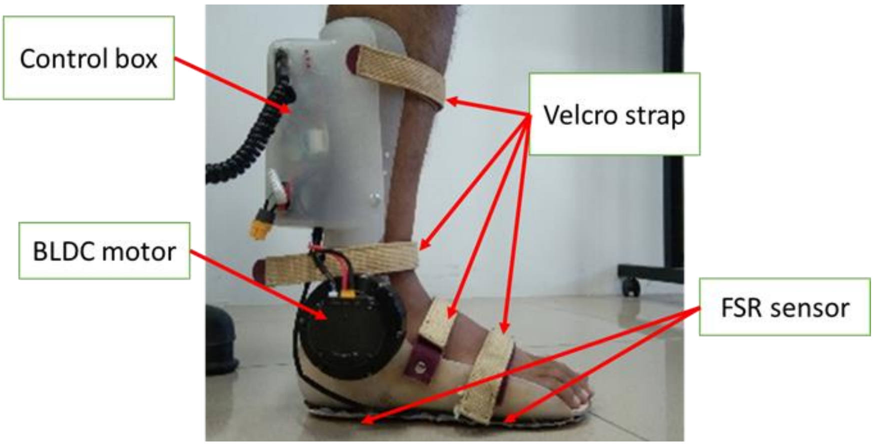

Figure 1. The Structure of the Robot AFO.

3.2 Flexion Control

The flexion control is straightforward, which are separated into the three modes of calibration, training, and walking. In the calibration mode, the controller will capture the standing ankle position and set it as the zero position, as shown in Figure 2. Dorsiflexion increases the ankle position, while plantarflexion decreases the ankle position. In the training mode, the robot AFO performs a continuous dorsiflexion and plantarflexion with a constant angular velocity, as shown in Figure 3 (a). The flexion begins with dorsiflexion until the ankle joint reaches the maximum dorsiflexion angle. Then, the robot AFO does a plantarflexion until it reaches the maximum plantarflexion angle. Here, the maximum dorsiflexion and plantarflexion are different for each person and must be set beforehand. Meanwhile, in the walking mode, the robot AFO must perform a dorsiflexion only at the swing phase. Figure 3 (b) shows the flow chart of the walking mode algorithm. First, the current gait detection is detected by the FSR. If the current gait phase is stance phase (P1 – P3), then the robot does nothing. On contrary, if the current gait phase is swing phase (P4), then the robot should perform the dorsiflexion until the maximum dorsiflexion angle to clear the toe during walking.

Simple P controller controls the ankle angular velocity (ω_{out}), as shown in Figure 4. Controlling the ankle velocity is proven to give useful support because it can dictate the appropriate torque indirectly [20].First, a reference (ω_{ref}) should be set beforehand. The error between the reference and the current ankle velocity is then calculated. Based on the error (e), the P controller generates a increment torque signal for the BLDC motor. Big error will be resulted in a big increment torque signal and vice versa. Finally, the torque generated by BLDC motor is increased by the amount of that increment. The ankle velocity (ω) is integration of the torque resultant in the ankle joint ($\Sigma\tau$) divided by the foot system inertia (I_f). The foot system inertia consists the foot, calf, and the robot inertia [20]. Meanwhile the torque resultant includes the torque from the foot system weight, foot force contacts on the ground and foot muscle force. Therefore, changing the torque will eventually alter the ankle velocity to be similar as the target ankle velocity.

$$\omega = \int \frac{\sum \tau}{I_f} \tag{1}$$

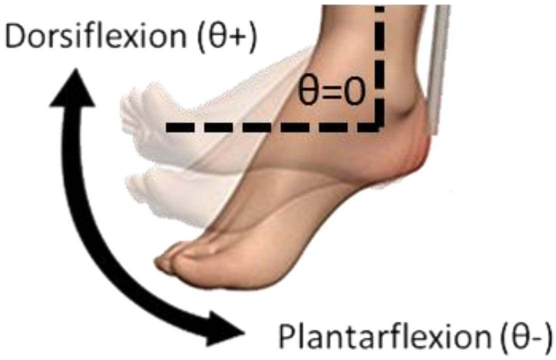

Figure 2. Ankle Position: Zero Position, Dorsiflexion and Plantarflexion.

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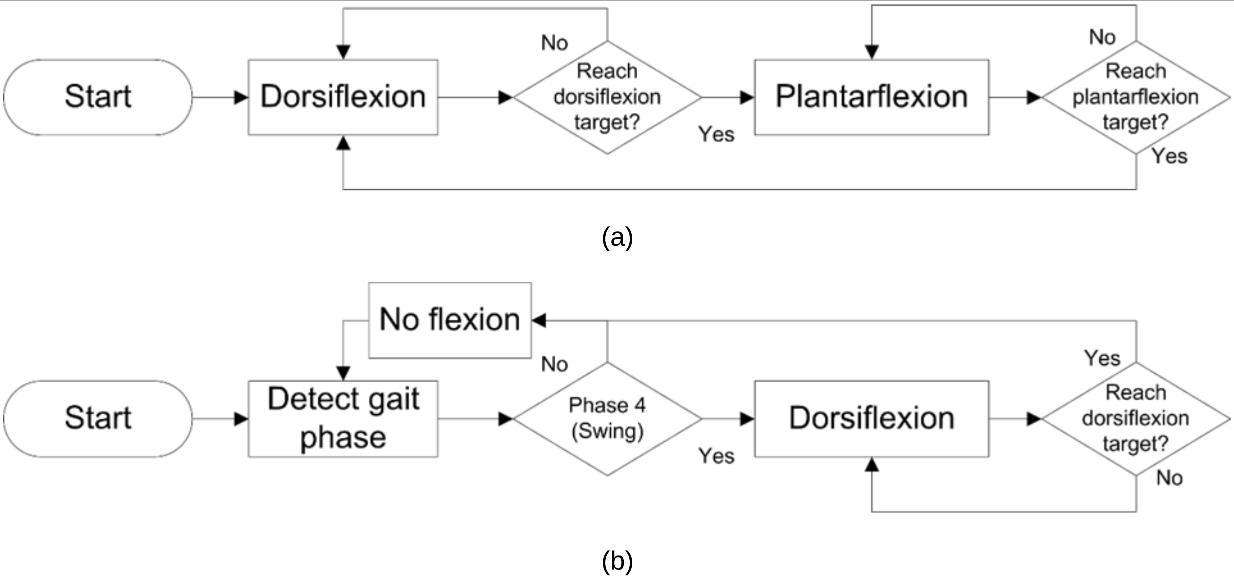


Figure 3. Robot AFO Algorithm Flowchart: (a) Training Mode; (b) Walking Mode

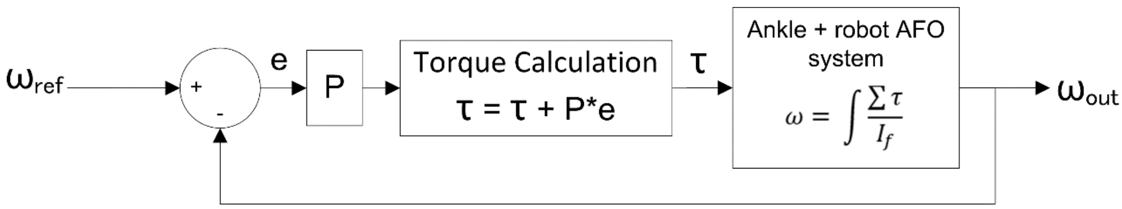


Figure 4. Proportional Controller to Control the Ankle Angular Velocity

3.3 Electronics System Design

The electronic system design mainly consists of sensor, actuator, and controller, as shown in Figure 5. The robot uses FSR on heel and toe to detect the gait phase. This kind of set up is popular for developing robot AFO because of its simplicity, yet accurate gait detection compares to other methods, such as bio signal, accelerometer, and other sensors [19]. The FSR is FSR 402 by Interlink Electronics with active area of 12.7mm2 and maximum measurement of 10 Nm. They are connected in voltage divider configuration to the controller. The voltage divider circuit is powered with 5V from the controller. The measured voltage (V_m) where R_m is measured resistor and R_{FSR} is the FSR resistance, is read by the controller. If there is a contact, then the FSR resistance will decrease, which will increase the V_m. Here, the R_m is 22 Ohm and the lowest R_{FSR} is 0.26 kΩ. Therefore, the maximum Vm that can be measured is 0.4 volt. Contact and non-contact heel or toe is identified by implementing V_m threshold value of 0.05 volt.

For the actuator, a BLDC motor AK-60 series by T-motor is employed. The motor is controlled using the Field Oriented Control (FOC) method and is equipped with 6:1 reduction ratio planetary gear to produces the necessary torque. The maximum torque is 18 Nm, as stated in the datasheet, which can be operated using 24V input voltage from the battery. The motor has rotary encoder and current sensing unit, so it can measure the current torque, position, and velocity of the motor. CAN protocol is used to communicate the motor controller and the robot AFO controller. The BLDC motor moves whenever the controller received command in the form of torque, position, or velocity value. The robot AFO controller is an Arduino UNO with additional CAN shield by DFRobot. The FSR voltage divider circuit is connected to the analog input, while the BLDC motor communicate through the CAN shield. The controller is powered by 24V battery, which regulated into 12V. There are three buttons for commands of mode selection, such as calibration mode, training mode and walking mode. Three mode indicators are available to see the current mode that are being selected.

$$V_m = \frac{R_m}{R_m + R_{FSR}} \times 5 \tag{2}$$

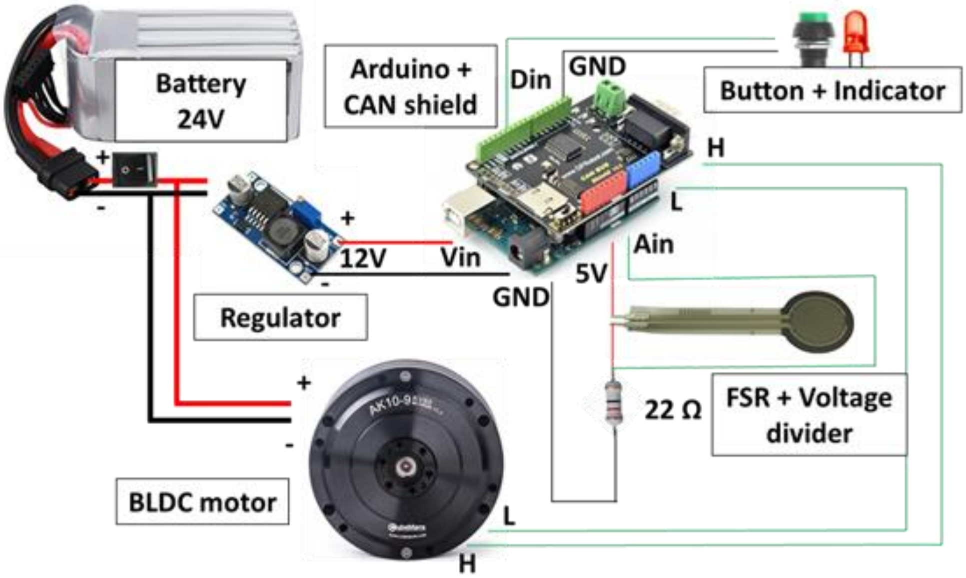


Figure 5. The Electronics System Design for the Developed Robot AFO.

3.4 Testing Procedure

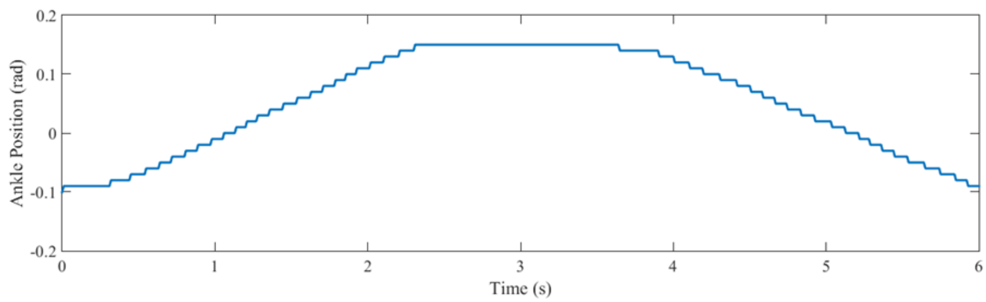
The robot AFO capability to perform the task in training and walking mode is tested. The robot will perform dorsiflexion and plantarflexion continuously in a constant angular velocity. There are three testing condition, such as no load, 1 Kg load, and foot load. The no load means the robot AFO perform the task as it is. The 1 Kg load is a dumble bar, which is placed at the toe part of the robot AFO to maximize the torque load. As for the foot load, the person should place the foot firmly by attaching the velcro strap with the heel touching the back of the robot AFO foot part. In this test, the target dorsiflexion and plantarflexion position are 0.15 rad and -0.1 rad respectively. Meanwhile, the ankle velocity target are 0.7 rad/s dorsiflexion and -0.7 rad/s plantarflexion. The gait detection is also tested by having a subject wear the robot AFO and performing the four gait phases (heel contact, foot flat, heel off, swing). All the data is recorded using Arduino serial monitor and moved to the excel for further processing and comparison.

4. Result and Discussion

4.1 Auto-Flexion with Constant Velocity

Figure 6, Figure 7 and Figure 8 show the testing result of the robot in three difference condition, such as no load, 1 Kg load, and foot load respectively. In general, all the results show that the algorithm in Figure 4 has been successfully being implemented. The dorsiflexion and plantarflexion stopped when the ankle position reach a certain target, which are 0.15 rad and 0.1 rad respectively. The produced torque also increases and decreases (oscillated) to control the ankle velocity according to the reference, as explained in Figure 5. More explanation on the result in each condition are follows.

Figure 6 shows the testing result of the robot AFO performing continuous flexion with no load. The ankle position moves as targeted. It goes up gradually from -0.1 rad to 0.15 rad (dorsiflexion), stay a bit, then goes down to -0.1 rad (plantarflexion). The dorsiflexion velocity is started from 0 rad/s then goes up to the 0.7 rad/s. The the ankle velocity is stayed at 0 rad/s before goes down to -0.7 rad/s to perform the plantarflexion. Since the target velocity is 0.7 rad/s, it is assumed that the robot AFO success to achieve the target velocity. To maintain the ankle velocity, it can be seen that the torque goes up and down in the range of 0 to 2 Nm for the dorsflexion and -2 Nm to 0 Nm for the plantarflexion.



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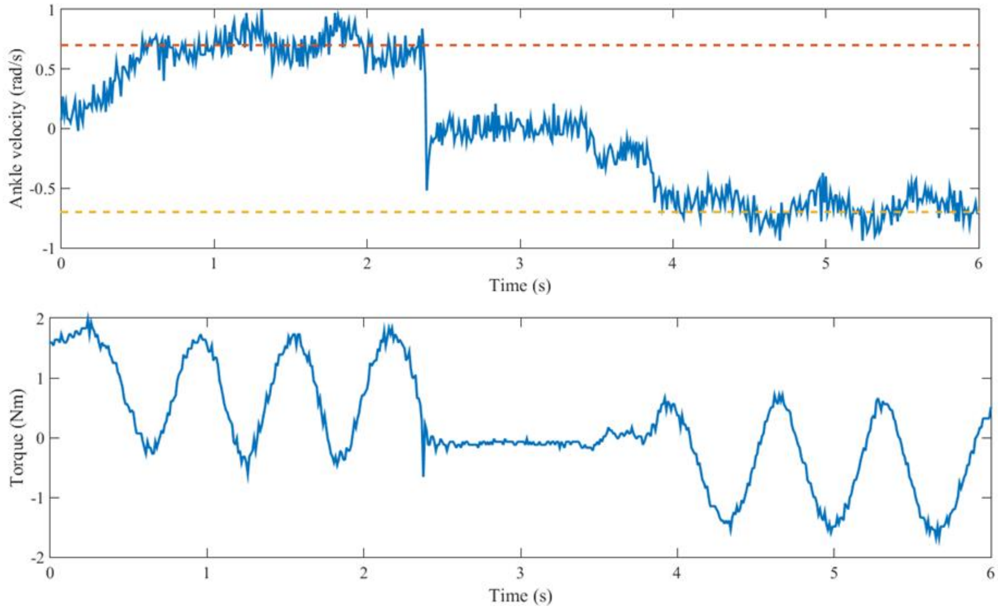
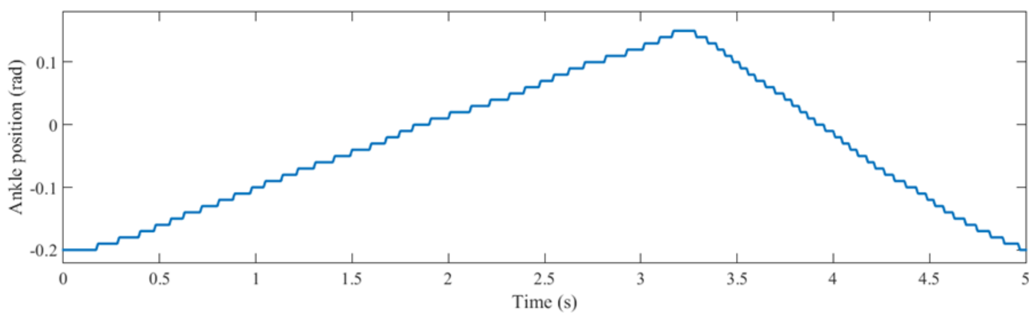


Figure 6. Testing Result with No Load: Ankle Position, Ankle Velocity and Torque of the Robot AFO.

Testing with 1 Kg load shows a different result, as shown in Figure 7. The ankle position reaches the target of 0.15 rad during dorsiflexion. But, it fail to keep the position at -0.1 rad. Instead, the plantarflexion stops at - 0.2 rad. The ankle velocity result also shows that the robot AFO does not follow the plantarflexion velocity target of - 0.7 rad/s. The ankle velocity stays at 0.7 rad/s on dorsflexion then dropped to -1.8 rad/s on plantarflexion. As for the torque, the robot AFO produces positive torque even during the plantarflexion. The lowest torque is 0 Nm and the highest torque is 4 Nm. Similarly, the torque value goes up and down to maintain the ankle velocity as close as possible to the target ankle velocity.

Meanwhile, testing the robot AFO with the real food produces more similar result to the 0 Kg load result. It can be seen from Figure 8 that the ankle position is goes up and down from -0.1 rad to 0.15 rad as wanted. The ankle velocity also successfully follows the target of 0.7 rad/s dorsiflexion and -0.7 rad/s plantarflexion. Although at the beginning of plantarflexion the ankle velocity exceeds the target, it can still recover to approach the -0.7 rad/s, which is a good indicator of controlled ankle velocity. The torque result is quite different with the result of testing with no load. It still goes up and down, but the torque in Figure 8 shows an increasing gradient on dorsiflexion and decreasing gradient on plantarflexion instead of stable osscilation.

The robot AFO successfully performing a dorsiflexion and plantarflexion. However, the ankle velocity control result needs to be discussed further. In general, the robot AFO can control the ankle velocity during the dorsiflexion, but not during the plantarflexion. There is no problem with no load conditions because the ankle velocity is accurately control to follow the target velocity. However, when a load is applied the robot AFO fails to control the plantarflexion velocity. Closer inspection on the torque graph shows that the robot produces negative torque initially, which is -0.3 Nm. It means the direction of the torque is the same as the direction of the load torque. As a result, the ankle velocity offset become too large that the robot AFO fails to recover in that short period.



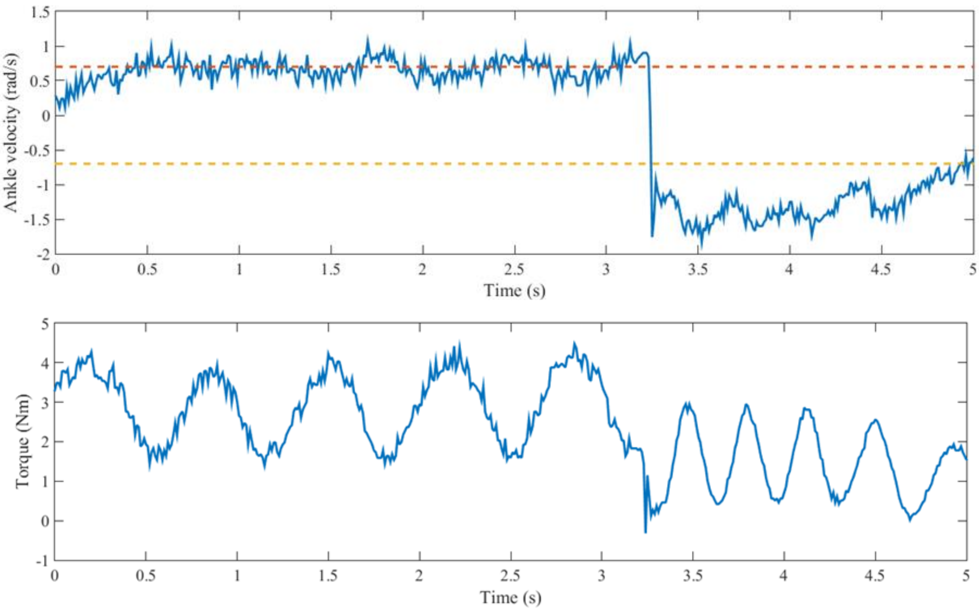
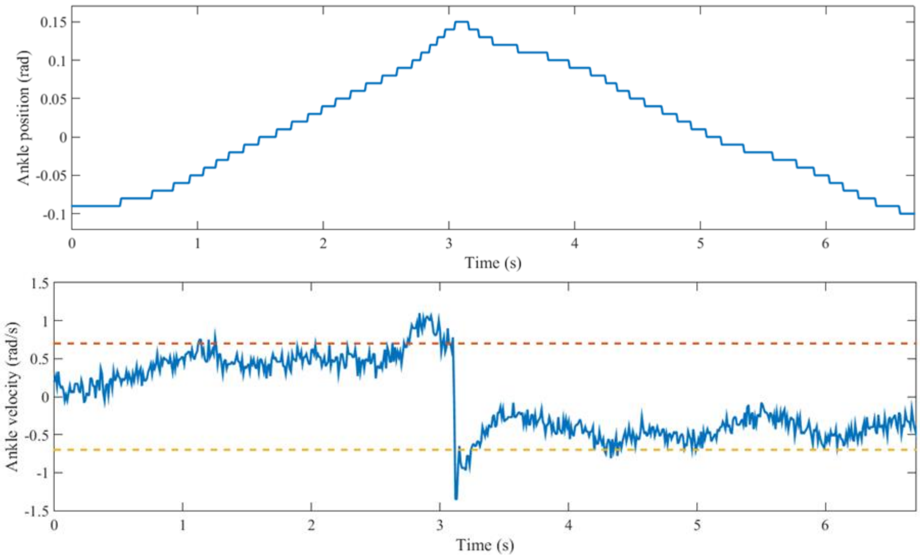


Figure 7. Testing result with 1 Kg load: Ankle position, ankle velocity and torque of the robot AFO.

Failing to maintain the ankle velocity also causing the ankle position exceeding the target. Figure 7 shows that the robot AFO plantarflexion is not stopped at -0.1 rad, but stopped at -0.2 rad. It stopped that not because of the robot AFO control, but because it is the limit of the robot AFO range of motion mechanically. Looking at the flowchart in Figure 4, the robot is maintaining the movements only. It does not have the algorithm to keep the position. Current algorithm only stopped the movement when a certain position is reached by the robot, as shown by the delay in the result of testing with no load in Figure 6. However, stopping the movement and keeping the position are different task. Therefore, future study should include the algorithm to keep the position when the robot AFO reach a certain position. In theory, the robot AFO should be able to do it since the maximum BLDC motor torque presented in this study is 18 Nm.

Meanwhile, the control capability to adjust the torque needs to be appreciated. The torque gradient changes when the load is not constant, such as the foot load. The foot muscle might exert some forces unconsciously, which make the load on the robot is not constant. When the load is constant, the robot AFO generates a stable oscillated torque. The torque oscillation shows that the controller could not find the keep the right amount of torque. But, in this research, the goals are to control the ankle velocity and the robot successfully achieved the velocity controls by altering the torque value. Future study can improve the controller by changing the P and adding I and D parameter. The output of the controller should also be changed to be the torque directly, instead of torque increment value. It is expected that the ankle velocity can be control without torque oscillation.



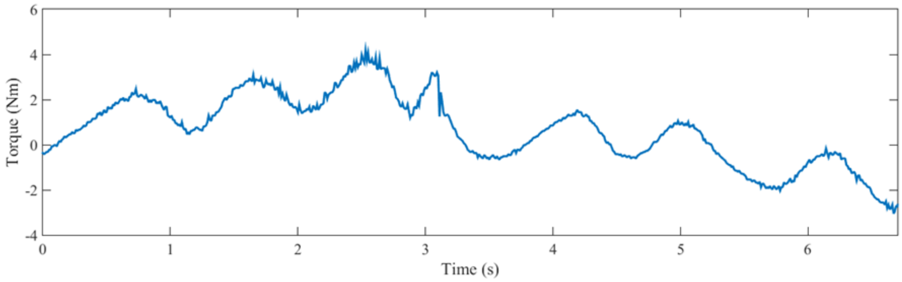
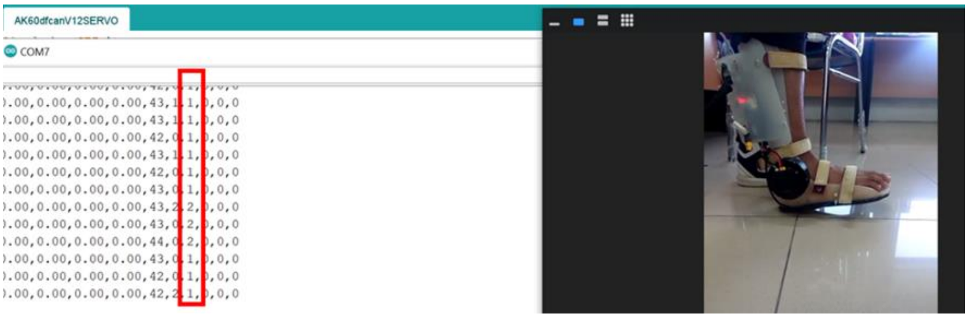


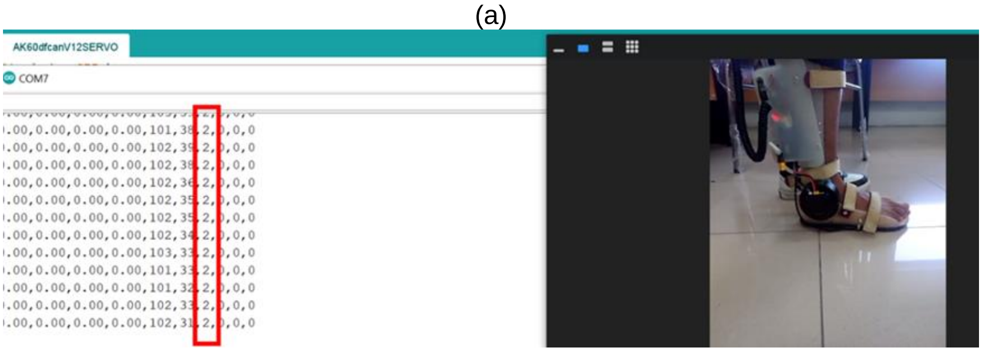
Figure 8. Testing result with foot load: Ankle position, ankle velocity and torque of the robot AFO.

4.2 Gait Detection

The auto flexion result is useful for the training mode of the robot AFO. As for the walking mode, the robot AFO should be able to detect the gait phase in addition to the ability of generating the flexion. Figure 9 shows the testing of the gait detection using camera and Arduino serial monitor. It can be seen that the robot AFO can detect the gait phase correctly. When the heel is in contact, the serial monitor shows the phase is one (Figure 9. a). The phase is shown to be two when all the foot contacts the ground (Figure 9. b). If the heels off the ground, then the serial monitor shows the phase is three (Figure 9. c). Finally, the phase became four in the serial monitor when the foot is off the ground (Figure 9. d). Since the robot AFO can detect the gait phase accurately, the robot AFO can support the flexion control during the walking mode.



(a)



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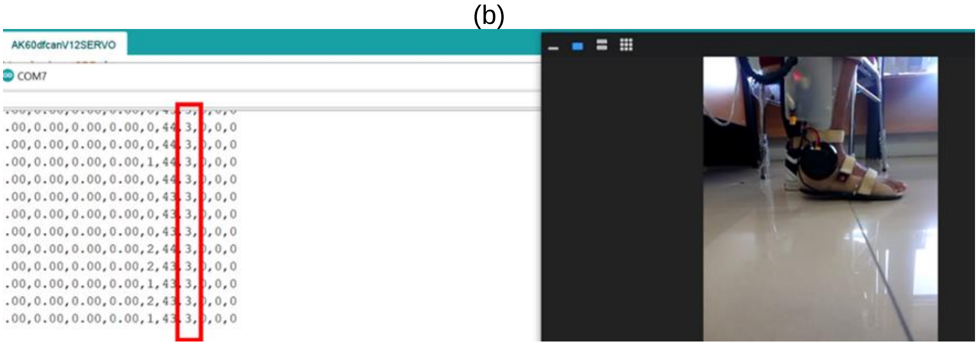

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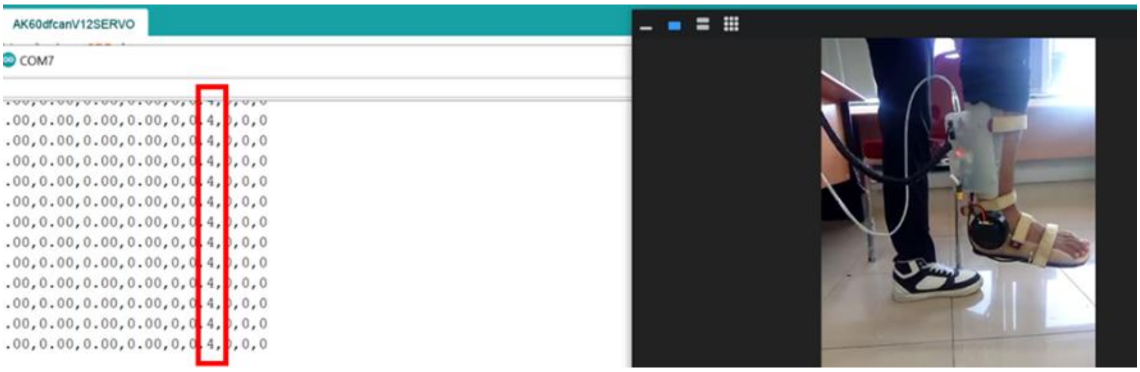

(d)

Figure 9. Testing result of the gait detection of the robot AFO: (a) Phase 1; (b) Phase 2; (c) Phase 3; (d) Phase 4.

4.3 The trade-off Between Complexity, Functionality and Cost

Functionality wise has been proven by the testing result in three conditions (no load, 1 Kg load and foot load). In terms of complexity, it can be said that the robot AFO design is simple enough as the numbers of actuator and sensor is minimum (one each) [21]. The controller box is attached at the back of the robot AFO structure, so as a whole the robot only has one body. The weight is also less than 1 Kg, which make the robot AFO is light to be wear. It can also be worn easily by strapping the foot in place using the Velcro strap. The current robot AFO prototype costs below IDR 30 million to build, which is cheaper compare to the commercial exoskeleton in the market place (Aliexpress). However, the existing product is intended for the whole lower limb support. Therefore, it cannot be compared directly and future study should investigate whether the developed robot AFO in this research is affordable by post-stroke patient in Indonesia.

5. Conclusion

In this research, a robot AFO with necessary function and simple design has been successfully developed. The robot AFO is build using a BLDC motor as the actuator and FSR as the gait detection sensor. The robot has three modes of operation, such as calibration, training, and walking mode. Testing has been done on the robot, where the results show the robot can perform the auto-flexion with constant velocity according to the velocity reference using the proposed proportional controller and can detect the gait phase accurately. Future study should be done in the control algorithm aspect, such as modifying the PID parameters and adding “keep in position” algorithm to improve the robot AFO functionality more. Study on the immediate effect on post-stroke patient is demanded for the next study before proceeding to the long-term effect. Lastly, the cost affordability is also interesting aspect to be investigated as has been pointed out in previous research by [16].

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References

[1] Pipit Mei Sari, Atika Mira Agniana, and Mohammad Saiful Ardhi, “Trends of ischemic stroke admission during two years of COVID-19 pandemic: A retrospective cross-sectional study at a tertiary hospital in Indonesia,” *Bali Medical Journal*, vol. 11, no. 2, 2022. https://doi.org/10.15562/bmj.v11i2.3498

[2] Yanti Srinayanti, Wina Widianti, Dian Andriani, Fidya Anisa Firdaus, and Henri Setiawan, “Range of Motion Exercise to Improve Muscle Strength among Stroke Patients: A Literature Review,” *International Journal of Nursing and Health Services (IJNHS)*, vol. 4, no. 3, 2021. https://doi.org/10.35654/ijnhs.v4i3.464

[3] World Stroke Organization, “Global Stroke Fact Sheet 2022.”.

[4] A. F. W. Ho *et al.*, “Association of ambient air pollution with risk of hemorrhagic stroke: A time-stratified case crossover analysis of the Singapore stroke registry,” *Int J Hyg Environ Health*, vol. 240, Mar. 2022. https://doi.org/10.1016/j.ijheh.2021.113908

[5] R. Xu *et al.*, “Association of short-term exposure to ambient air pollution with mortality from ischemic and hemorrhagic stroke,” *Eur J Neurol*, vol. 29, no. 7, pp. 1994–2005, Jul. 2022. https://doi.org/10.1111/ene.15343

[6] Y. Bae and D. Park, “Immediate Effect of Lower-Leg Kinesio Taping on Ankle Dorsiflexion and Gait Parameters in Chronic Stroke with Foot Drop,” *Journal of Stroke and Cerebrovascular Diseases*, vol. 31, no. 5, May 2022. https://doi.org/10.1016/j.jstrokecerebrovasdis.2022.106425

[7] A. Pramudita Putra, A. Rahmatillah, N. Khafidotur Rodhiyah, and I. Putu Alit Pawana, “Computational Analysis of Ankle-Foot Orthosis for Foot Drop Case During Stance Phase in Gait Cycle,” Journal of Engineering Science and Technology, vol. 17, no. 2, pp. 985–0996, 2022.

[8] G. Liu, F. Gao, D. Wang, and W.-H. Liao, “Medical applications of magnetorheological fluid: a systematic review-IOPscience Medical applications of magnetorheological fluid: a systematic review,” 2022. https://doi.org/10.1088/1361-665X/ac54e7

[9] Di. Adiputra, M. A. A. Rahman, Ubaidillah, and S. A. Mazlan, “Improving passive ankle foot orthosis system using estimated ankle velocity reference,” *IEEE Access*, vol. 8, pp. 194780–194794, 2020. https://doi.org/10.1109/ACCESS.2020.3033852

[10] C. M. Thalman, T. Hertzell, M. Debeurre, and H. Lee, “Multi-degrees-of-freedom soft robotic ankle-foot orthosis for gait assistance and variable ankle support,” *Wearable Technologies*, vol. 3, p. e18, Aug. 2022. https://doi.org/10.1109/ACCESS.2020.3033852

[11] J. Inoue *et al.*, “Development of a Gait Rehabilitation Robot Using an Exoskeleton and Functional Electrical Stimulation: Validation in a Pseudo-paraplegic Model,” *Prog Rehabil Med*, vol. 7, no. 0, p. n/a, 2022. https://doi.org/10.2490/prm.20220001

[12] M. Pan *et al.*, “Soft Actuators and Robotic Devices for Rehabilitation and Assistance,” *Advanced Intelligent Systems*, vol. 4, no. 4, p. 2100140, Apr. 2022. https://doi.org/10.1002/aisy.202100140

[13] X. Tang *et al.*, “A Wearable Lower Limb Exoskeleton: Reducing the Energy Cost of Human Movement,” *Micromachines*, vol. 13, no. 6. MDPI, Jun. 01, 2022. https://doi.org/10.3390/mi13060900

[14] H. Mastrisiswadi and Herianto, “Analisis Kebutuhan Robot Rehabilitasi Pasien Pasca Stroke dengan Menggunakan Metode Kano,” *Jurnal Ilmiah Teknik Industri*, pp. 151–156, 2016. https://doi.org/10.23917/jiti.v15i2.2331

[15] Takehito Kikuchi, Sousuke Tanida, Takashi Yasuda, and Takamitsu Fujikawa, “Automatic Adjustment of Initial Drop Speed of Foot for Intelligently Controllable Ankle Foot Orthosis,” 2013. Accessed: Oct. 10, 2022. https://doi.org/10.1109/EMBC.2013.6609504

[16] T. Slucock, “A Systematic Review of Low-Cost Actuator Implementations for Lower-Limb Exoskeletons: a Technical and Financial Perspective,” *J Intell Robot Syst*, vol. 106, no. 1, Sep. 2022. https://doi.org/10.1007/s10846-022-01695-0

[17] E. Esfandiari, H. Saeedi, A. Ahmadi, M. Jalali, A. Mohammad Pour, and V. Abdollah, “Investigating the effects of conventional thermoplastic ankle-foot and the neoprene ankle-foot orthoses on the kinetics and kinematics of gait in people with foot drop following traumatic injury of the peroneal nerve: A pilot study,” *Foot*, vol. 50, Mar. 2022. https://doi.org/10.1016/j.foot.2021.101898

[18] F. Hasan, Q. Murtaza, M. Varshney, and F. Hasan, “Design and Analysis of a Custom Ankle Foot Orthosis (AFO) with Foot Drop Patient,” 2022, pp. 187–197. https://dx.doi.org/10.1007/978-981-16-2229-8_20

[19] D. Adiputra *et al.*, “A review on the control of the mechanical properties of Ankle Foot Orthosis for gait assistance,” *Actuators*, vol. 8, no. 1. MDPI AG, 2019. https://doi.org/10.3390/act8010010

[20] D. Adiputra *et al.*, “Control reference parameter for stance assistance using a passive controlled Ankle Foot Orthosis-A preliminary study,” *Applied Sciences (Switzerland)*, vol. 9, no. 20, Oct. 2019. https://doi.org/10.3390/app9204416

[21] D. Adiputra, M. Azizi Abdul Rahman, I. Bahiuddin, Ubaidillah, F. Imaduddin, and N. Nazmi, “Sensor Number Optimization Using Neural Network for Ankle Foot Orthosis Equipped with Magnetorheological Brake,” *Open Engineering*, vol. 11, no. 1, pp. 91–101, Jan. 2020. https://doi.org/10.1515/eng-2021-0010