International Journal of Advanced Science and Technology
Vol. 29, No. 6s, (2020), pp. 860-872

Performance Analysis for Sprain Ankle Rehabilitation System Using Gyro Sensor

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Abstract

Sprain ankle rehabilitation is an exercise to recover full function without limitations and strength of ankle joint under the therapist exercise. Recently, ankle rehabilitation technique is enhanced using an intelligent system compared to a conventional technique. Patients mainly perform ankle exercise by manual therapy can cause a loose interest for them to continue the activity. The objectives of this study are to propose and develop an ankle rehabilitation system platform that acts as a user-friendly device able to execute an ankle with 3 Degrees of Freedom (DoF). The develop device consists of a microcontroller, servo motor, gyro sensor, Wi-Fi Module and Graphical User Interface. The microcontroller connected via internet connectivity with smartphones to control modes of exercise at different speeds according to the user's circumstances. A gyro sensor is embedded onto the robotic platform in order to measure the limitation position angle of the patient's. The closer the tilt angle achieved reflects the recovery which near to the normal person. The strength movement of ankle ability given by each participant almost 55% able to achieve the limitation range angle for the lower torque stiffness power supply of the servo motor. For higher torque stiffness power supply, almost 35% of each participant's able to reach the limitation range of movement. Based on the result obtained, the Ankle Rehabilitation System device manages to help significantly or almost fully improve the time healing of sprain ankle patients with more interesting motorized rehabilitation devices compared to a traditional device.

Keywords: *Rehabilitation Robots, Ankle Rehabilitation, Ankle Sprain, Assisted Therapy*

1. Introduction

A sprained ankle, also known as ankle ligament injury commonly occurs for the lower limb musculoskeletal injury by an individual because of overexertion or turned unexpectedly movement direction [1][2]. Several studies have revealed that a sprained ankle injury can happen to almost everybody especially to active people who are vulnerable to ankle sprain injuries [3][4][5][6]. [7] states that the athletes or people who actively conduct the warm-up or stretching as daily routines exercise will have less probability to have an ankle injury. Previous research has shown the purpose of stretching is to model of an ankle-foot structure which most common athletes suffered [9]. Based on the foot structure, inversion or internal rotation is the most common people will get an injury. [10] In their narrative review, the early injury will occur is the anterior talofibular or tibiofibular ligament then followed by an injury to the calcaneofibular ligament.

The ankle bends more than normal position cause injury or damages severity to the ankle ligament which can stretch or tear either partially or fully in the worst situation [11]. The basis damage severity of ankle ligament sprains is graded from I to III stages. Grade I is a mild stretching of the ligament that doesn't cause heavy macroscopic rupture or joint

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instability. Grade II is considered as moderate partial rupture of the ligament which causes moderate pain and swelling but has functional limitation and also a slight to moderate instability. Usually, this stage will present for patients who have a problem with weight-bearing. Grade III is a totally severe ligament rupture with marked pain, swelling, hematoma, and decreasing instability function [12]. Normally, the ligament needs six weeks to heal although the rates of everyone to recover are different but depend on ankle sprain level [13].

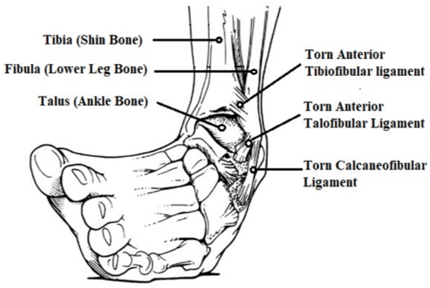

Figure 1. The Model of an Ankle-Foot Structure [9]

According to [14], rehabilitation is the mainstay treatment for patients who suffer from ankle injuries. A study by [15] mentioned that functional treatment will improve with faster recovery in order to regain full function strength of ankle joint under therapist exercise compared to immobilization. In this rehabilitation, there are two types of technique which are by manual rehabilitation or robotic rehabilitation. The manual rehabilitation used simple devices for rehabilitation such as elastic bands, roller foams, and wobble boards. [16] state that robotic rehabilitation used mechatronic devices need to concern the mechanical design, programming, control, safety, and man-machine interfaces. This innovation in robotic rehabilitation is to reduce the need of human manpower and help to assist the routine work with more precision.

In order to measure the instant change of angle during a rehabilitation session, the gyro sensor is used which requires less energy and not sensitive to magnetic disturbances. It is undeniable why there are many gyros used in smartphones and [17] has implemented a wireless gyro sensor platform to records the ankle rehabilitation system's therapy usage with wireless transmission via Internet connectivity. The gyroscope is also used to monitor compliance of exercise instruction, evaluate treatment efficacy and real-time monitoring feedback with more reliability in the measurements of angle by [18].

The objectives of this paper are to develop a prototype of an ankle rehabilitation system using servo motor wirelessly via the Internet of Things (IoT) connectivity between the ankle rehabilitation systems with the Android device. An assessment is a conduct to analyze the performance of the system based on the patient's feedback in order to increase muscle force and joint stability.

The paper is organized as follows. Section II describes the existing sprain ankle rehabilitation. Followed by Section III introduced the operating principle and design process of sprain ankle rehabilitation system using gyro-meter and servo motor as the actuator. Section IV concentrates on the experimental validation process and result discussion. Section V describes the conclusions.

2. Existing Sprain Ankle Rehabilitation

This section discusses the existing sprain ankle rehabilitation system either by using the manual or robotic therapist. This explains the difference usage between both method devices.

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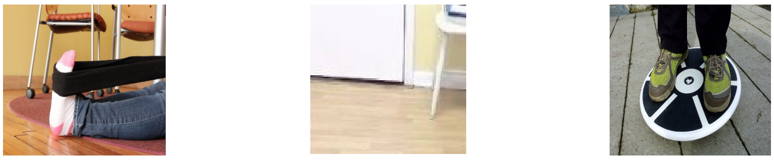
2.1. Manual Devices Rehabilitation

The manual therapist use easy and simple devices which could be find at any physiotherapist outlets to perform the rehabilitation activity at their convenient places. *Figure* 2 shows an example of simple devices used for rehabilitation such as elastic bands, roller foams, and wobble boards. One of the simplest devices is elastic bands used for muscular strengthening which made of resistive elastic. Roller foams are used to improve the balance and proprioception that have unstable surfaces. Furthermore, wobble boards are used to improve balance and proprioception. All this three devices can help to improve the stability and strength of ankle patient. However, [19] stated that these low complexity devices or primitive passive devices only allow simple rehabilitation activity using the patient's effort and not able to perform any data acquisition of a patient's exercise.



(a) Elastic bands (b) Roller foams (c) Wobble boards

Figure 2. Example Exercise with an (a) Elastic Band; (b) Roller Foams; (c) Wobble Boards

2.2. Robotic Devices Rehabilitation

Currently, the revolution of robotic has immerged the system technology for assisted operations devices in term of functional activity exercise instruction, wireless system communication, real-time feedback monitoring and sensor used to read the accuracy of angle rotation [20][21]. In this ankle rehabilitation system, the design element is a concern for three parameters which consists of the degree of freedom for tilt ankle motion, type of actuator and collect data method for the rehabilitation system.

a) Degree of Freedom for Sprain Ankle Motion

Figure 3 shows the joint motion of the ankle rotation structure and range of motion for each degree of freedom, as stated in *Table* 1. The ankle joint motion rotates three axes x, y, and z. It is a fixed Cartesian coordinate that represents a rotating pivot in three different directions [22]. In this study, the degree of freedom is the range that patients need to achieve during the exercise treatment to heal their injury such as a normal person based on the ankle physiological data. The angular velocity needs to be considered to ensure the patients can follow the therapy exercise and feel comfortable.

Previous technology of ankle rehabilitation system is with one Degree of Freedom (1-DoF) is focused on the y-axis for assisting dorsiflexion and plantarflexion as the main contributor for propulsion. Examples for modern ankle exoskeletons with one active DOF are PPAFO from University of Illinois by [23], KAFO from National University of Singapore by [24], Proprioceptive Neuromuscular Facilitation (PNF) from Peking University by [25], Machine of Hemiplegia from Rangsit University by [26], Straight Legged Raise (SLR) from Texas Tech University by [27] and AFO from Savitribai Phule University by [28]. Two Degrees of Freedom (2-DoF) is the less footwork exercise given to patients, but it is the simplest and the less number of the actuator to move the platform. It can only control the tilt angle of the feet using the platform to x-axis and y-axis or any other combination of two axes (2-DoF) only [29][30][31][32].

Six Degree of Freedom (6-DoF) has more footwork compare to three Degrees of Freedom (3-DoF) but will be too complex and need a lot of actuators to control. It also

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will increase the price but based on six degrees of freedom analysis shows better captures the energy changes of the body than more conventional three degrees of freedom estimates.

Figure 3. Model of Ankle Structure with the Movement

In this design, the positions or angle of the ankle about three orthogonal anatomical planes or 3-Degrees of Freedom (3-DoF) will be designed to combine all three movements of plantarflexion/dorsiflexion rotation, internal/external rotation and inversion/eversion rotation. Previous studies reported the angle range must accurate to make sure the ankle is in a good position and recovers the injury of sprain ankle patients [33][34][35].

Table 1. Ankle Range Limitation Data [33][34][35]

Servo Motor	Joints Motion	Angle Range (degree)	Angular Velocity (degree/S)
1 (x-axis)	Inversion	0º ~ (40º ~ 50º)	<100
	Eversion	(-25º~ -30º) ~ 0º	
2 (y-axis)	Dorsiflexion	0º ~ (25º~ 30º)	<60
	Plantarflexion	(-40º~ -50º) ~ 0º	
3 (z-axis)	Abduction	0º ~ (25º ~ 50º)	<40
	Adduction	(-25º~ -50º) ~ 0º	

b) Actuator for Sprain Ankle Rehabilitation System

The actuator is a component that provides power to perform movements for the Ankle Rehabilitation system as stated by [36]. There are many advantages to the servo motor compared to other actuators. One of the advantages of the servo motor is it easy to manipulate and programmed by the Arduino board. Furthermore, servo motor can provide the application with higher controllability and performance with the best long-term productivity investment [37]. Servo motor also has required position feedback with more complexes to control. In comparison to a stepper motor, the servo motor is small in size and has no vibrate but still can handle the work given. The high speed and high torque are not easy to achieve for the stepper motor. Next, pneumatic also can use as the actuator but the cost is much more expensive and complicated to implement in the system because need some extra components to make it functional. Pneumatic is costly and complex for the setup equipment and has low force and speed. Servo motor is smaller but still can give the same torque.

c) Gyro Sensor to Read the Tilt Angle

Gyro sensor is useful for an inertial navigation system for continuously calculating current position, orientation and moving velocity of an objects. There are some of the common Gyro-Meter that has been used is Micro-Electro-Mechanical Systems (MEMS),

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a ring laser, fiber optic, and quantum. The most suitable type of Gyro-Meter to be used in this research is the MEMS type which contains a MEMS accelerometer and gyroscope. As proposed in [38], a method used the MEMS accelerometer (ADXL345) and gyroscope (L3G4200D) where is able to link through wireless link to a workstation and process the sensor stream data in real-time. It has stated by [39] that apart from the cheapest cost, the size of the MEMS type is almost the same as a coin and light in weight. In addition, the power from the Arduino is compatible and readily available for the MEMS.

3. Methodology

This section describes the process of the Ankle Rehabilitation System (ARS) to analyze the performance of the system based on the patient's feedback in order to increase muscle force and joint stability. *Figure* 4 shows the overall process for the ARS which consists of understanding the fundamental of this project by doing research. The methodology design of ARS is divided into two faces which is design the hardware and the software of the system. The first part is designing the hardware that needs to compatible with the software part. For the simulation part, the microcontroller was programmed using Arduino software then can upload the completed program to the Arduino microcontroller board. The gyro sensor (MPU-6050) embedded at the robotic platform will transmit the data value of the angle and save it into a document. An application in a smartphone will be used to control three servo motor (MG-995) different speeds of the actuator for passive movement wirelessly via internet connectivity. The output will through the process of a simulation test bench to ensure there is no offense allowed.

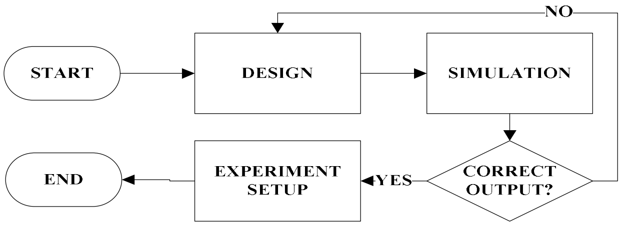

Figure 4. Overall Process Flow Chart for the Ankle Rehabilitation System

During the experiment setup, the Arduino microcontroller will connect with the Graphical User Interface (GUI) application that has been created in order to collect data and send it to a document to identify the tilt ankle angle of the patients. The user will put their feet on the robotic platform and follow the process of rehabilitation exercise. It can choose either to do the process of active movement or passive movement exercise. From here the therapy can identify the closer angle achieved that reflects the recovery of the patients near to the normal person actual angle.

3.1. Design

Figure 5 shows the design is separated into two parts which consist of hardware and software. The hardware design basically focused on the construction of ankle rehabilitation. The other part is designing the software such as programming the microcontroller using Arduino Software to move the servo to the step angle needed control by a smartphone using Blynk Application and data collection.

a) Design Hardware of Ankle Rehabilitation System

Figure 6 (a) shows the isometric drawing in the South-West (SW) view and (b) shows the North-East (NE) view. The width of the base would be in 34 centimeters and the

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width of the foot platform is in 29 centimeters for references. Based on the design of the foot platform, it can be applied for a person with length from 9 inches (23cm) until 11 inches (29 cm). The constructions of the prototype focus on low- cost, lightweight and easy to use both for patients and physical therapists. Thus, the base of the prototype must be larger than the ankle platform for stability. The weight of each person would influence the design of the prototype.

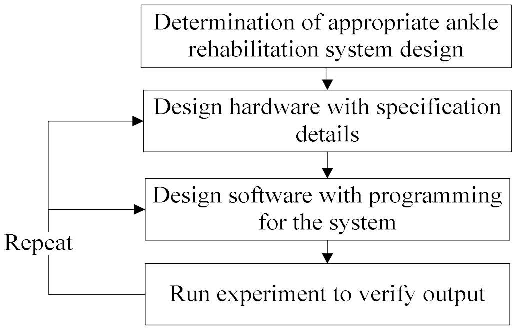

Figure 5. Overall Design Flowchart of the System

(a) South-West Isometric View (b) North-East Isometric View

Figure 6. Isometric View Drawing of SW and NE

Figure 7 shows the actual design of the prototype ankle rehabilitation system. Aluminum steel material is the best option for a solution to fabricating the hardware. The size of the aluminum is 2.5cm that will have minimal deflection and stress under maximum weight application (98 kg). The aluminum is cut into the dimension that has designs on the conceptual mechanical design developed in AutoCAD software. At each part of the mechanical construction, the rubber will be used to cover the end of the aluminum cut place to ensure not give injury to the user.

b) Design Software of Ankle Rehabilitation System

By designing the user interface for the Blynk application, setting the serial output signal from the application via internet communication. Programming the Arduino microcontroller board makes it compatible with the data serial send from a smartphone and the desired output signal for the servo motor to function from the serial data received. Next, design the Graphical User Interface for the data collection in real-time using Microsoft Visual Studio and save the patient's data for future analysis.

i) Blynk Applications

Blynk application is developed according to the desired design and select component needed that has been prepared in the application. *Figure* 8 indicates the design on the Blynk application after all the settings are done as the button used to control the servo motor on the microcontroller. The type of button needs and set the digital-analog pin in the widget. This widget created complete the structure of the software development where the application can successfully use to control the servo motor and connected with the Wi-Fi Module via the internet.

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ii) Graphical User Interface for Data Collect

Figure 9 illustrate the flowchart process of capture data from Arduino software into Microsoft Excel while Figure 10 shows the application that has been created. Microsoft Visual Studio is an Integrated Development Environment (IDE) compatible with many different languages but remains the same application functionality. This Graphical User Interface is created in order to capture the data in real-time during the physiotherapist exercise. Next, the data will be processed to show the maximum and minimum angle that the closer angle achieved reflects the recovery that near to the standard normal person. When the microcontroller is connected into the computer-based, the applications "Data Analysis" is open then press the scan port in order to recognize the com port connection of the Arduino microcontroller. After that, during the "Connect" button is pressed, data capture start the process to collect data from the microcontroller and appeared the value of ankle angle's reading at the column. At the same time, the chart construct the graph based on the value from the serial monitor for the maximum and minimum angle tilt angle. Thus, when the button "Disconnect" is pressed, the data is terminated the process and data is transferred to Microsoft Excel under the file name "Data Analysis". Lastly, the graph is being plotted inside the document and saved for any documentation or analysis.

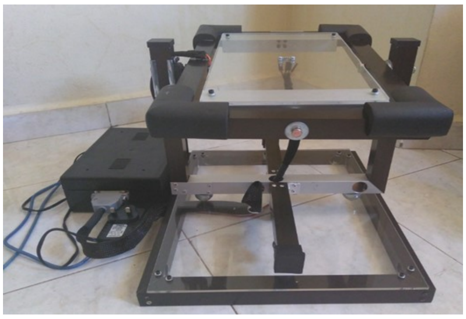

Figure 7. Construction Design of Hardware

Figure 8. Widget Created in the Blynk Application.

3.2. Simulation Test Bench

Figure 11 shows the simulation test bench for each important part of the ankle rehabilitation system for the purpose to verify the design is running without any error. This part is to ensure there are no injuries that will occur during the rehabilitation session for the safety purpose and the robotic platform able to work well during therapy exercise.

a) Test Connection between Application and Platform

The Arduino platform is connected with the Blynk application via Internet connectivity. The Internet needs to connect between widget applications with microcontrollers to control each servo motor of the Ankle Rehabilitation System platform. Next, simulation start with triggered the first button to move the z-axis servo motor control then followed by the next button which is to control the y-axis rotation and x-axis rotation.

b) Test the Angle Rotation of Each Servo Motor

Based on the ankle range physiological data, each servo has been programmed the limitation angle to avoid any error during rehabilitation sessions to avoid injuries. Each servo moves to 3 step axis which can execute ankle inversion/eversion rotation (x-axis), dorsiflexion/plantarflexion rotation (y-axis) and internal/external rotation (z-axis).

c) Test the Speed Rotation of Each Servo Motor

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The speed rotation of servo is control from the button in Blynk application with different speed modes. This speed control is important for the user from the early stage of injuries until the recovery stage which is the faster speed.

d) Test the Gyro Sensor Functionality

The gyro-meter is placed at the bottom of the foot platform and connected to the Arduino microcontroller. During the treatment process, it will move according to the foot platform and detect the real-time angle of movement. The reading data will display on the serial monitor to monitor the data angle have any error or not.

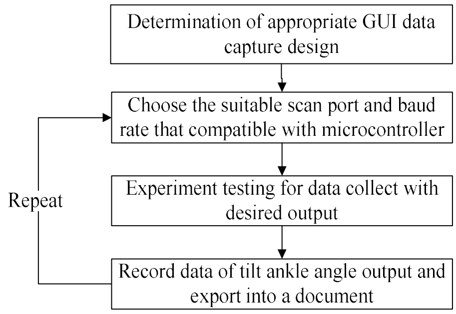

Figure 9. Design of Overall Graphical User Interface for Data Collection

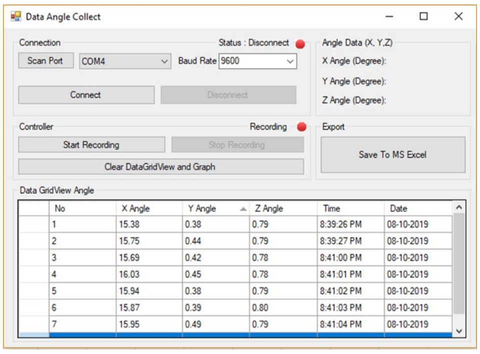

Figure 10. The Graphical User Interfaces Record Data Platform

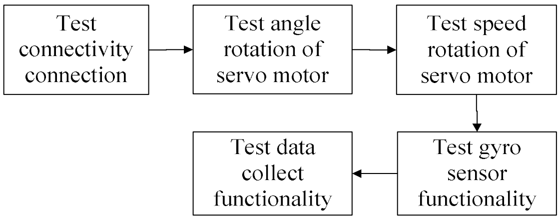

Figure 11. Test Bench Process to Ensure No Error Occurs

e) Test the Graphical User Interface for Data Collect

The Graphical User Interface will connect serial with Arduino microcontroller and display the angle value number. Then, all data are transferred to Microsoft Excel under the file name "Data Analysis".

3.3. Identify Output

The programmer needs to check the outputs for the overall process is the same as expected without any error. This needs to follow all the simulation test bench that has been discussed before. If not, each process needs to recheck again until the correct output is obtained.

3.4. Experiment Setup

Figure 12 depicts the situation during the analysis were taken with 5 different people. The experiment conducts as the participant places their foot onto the platform at 90 degrees from their sitting place. *Table* 2 shows the characteristics of the participant taken for the analysis have different weights and different foot sizes length. By collecting all the data from numerous of the person, the analysis is separated based on two types of movement which is a passive movement and active movement. The microcontroller connects with a smartphone via the internet in order to control the servo motor in terms of speed and angle rotation. Then, the real-time data will be collected for analysis data.

The active movement focus on the ability of the person to force the platform until reaching the maximum range of movement angle. Different torque stiffness power supply of 2 Amperes and 3 Amperes was used as the manipulated variable to give a different torque of stiffness for the servo motor. Thus, the two elements have different exercises but maintain the focus on regaining the muscle force and the stability of the ankle.

3. Experimental Validation Process and Results

This section discusses the experimental validation process during data collection and the output result analysis. Based on the result that has been developed by [33] and [34], the ankle physiological data is being referred to as the reference angle range of motion. The range angle of passive movement is set to ensure the platform is in the safe tilt angle range without any error during therapy exercise. It is necessary to test each function before the exercise process. By collecting the data from numerous participants, the analysis is separated based on two types of movement which is a passive movement and active movement. The inclusion criteria for the participants were no upper extremity diseases, no sensory deficits, no limited range of motion (RoM), and no psychological or emotional problems. Each participant was asked to do repetition with an attempt 50 times for accuracy data collection. From the 50 times attempt data then will generate for the mean which will be the result output data for each participant. From the 50 times attempt data then generates for the mean which will be the result output data for each participant.

4.1. Positioning Accuracy for Passive Movement with No-Load Analysis

Passive movement is controlled by the movement of external agency or a movement that is affected entirely by the therapist without the assistance of the patient's muscles. The test of positioning accuracy starts with no-load to avoid any injury incident before start with a real person's foot on the platform. *Figure* 13 shows the result of positioning accuracy without load for passive movement. It can be observed that the position during the platform is running close to the position target, which shows good accuracy of the control system.

4.2. Positioning Accuracy for Passive Movement with No-load Analysis

From this passive movement, analysis can observe the performance of the ankle rehabilitation system that has been completed in terms of body structure and servo motor as the actuator. The participants need to follow the movement of the servo motor in order to regain the normal angle range of movement such a normal person. *Figure* 14 indicates the passive movement to the actual trajectory for each person for the mean data from 50 times attempt data collection.

Figure 12. The Situation During the Analysis was Taken

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Table 2. The Characteristics of the Participants

No. Person	Age (Years)	Body Weight (Kg)	Foot Size Length (cm)
1	24	67.9	23.5
2	24	75.3	24.0
3	24	84.1	25.5
4	24	98.0	26.0
5	24	95.2	25.0

Based on the result in *Figure* 14, it shows that the servo motor that controls for Inversion/Eversion (x-axis) and Dorsiflexion/Plantarflexion (y-axis) doesn't have any problem in order to assist the platform to the actual angle trajectory even there is a load or no-load. Servo motor that needs to assists in Adduction/Abduction (z-axis) during there is no load, it can achieve the actual target angle. Nevertheless, it cannot be achieved to the actual angle trajectory if there is load by each person during Abduction/Adduction. Based on the observation, the servo motor of the z-axis has the highest load in order to carry the platform for the x-axis and y-axis actuation and load from the foot placed during a rehabilitation session. Maybe this can improve by using a Proportional Integral Derivative (PID) controller or closed-loop feedback mechanism to achieve the target angle in the future. Otherwise, the servo motor needs to change with the highest power specification.

4.3. Active Movement with Load Analysis

The active movement focus on the ability of the participants to force the platform until reaching the maximum range of movement angle. Active movement exercise is given which separate into two stages for mild and moderate patients in order to improve the strength muscle. Different torque stiffness using a different current in the range of 2 and 3 amperes of the power supply as the manipulated variable. *Figure* 15 and *Figure* 16 indicates the active movement to the actual trajectory for low and high torque stiffness that attempts from each participant after 50 times repetition exercise. The exercise can determine the maximum angle range of movement by each participant. Thus, the comparison must be made as the observation to determine the prototype is suitable or not for the patient to use for exercise.

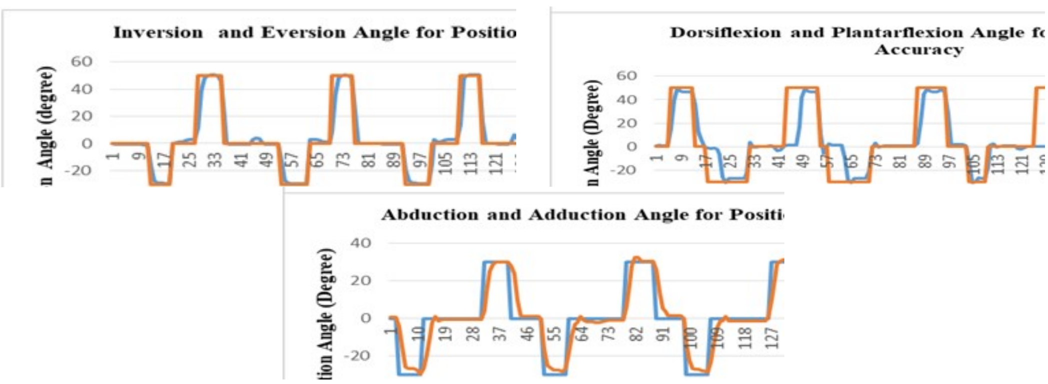

Figure 13. Result of Positioning Accuracy without Load for Passive Movement

Figure 15 and *Figure* 16 shows the data graph output has a different maximum angle reach by each participant for low (2A) and high (3A) torque stiffness current power supply. It can be proved that the low torque stiffness power supply gives less torque stiffness but has the highest achieved angle for the participants to push the platform using their ability ankle strength compared to high torque stiffness power supply. The other

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observation also can be concluded that the weight of the person will affect the achieved angle but not so much depends on the strength of the participants. Participant 1 until participant 3 has a different weight of the body but in the normal range of weight body. The data shows an increasing maximum angle achieved of participant 1 until participant 3 compared to participants 4 and 5 give more different tilt angle range achieved because of their weight is much higher. The other conclusion that makes difference in this data analysis which shows that participant 4 has the higher weight of the body doesn't mean it will give the highest result angle trajectory can be achieved compared to participant 5. This shows that the angle trajectory to push the platform can be achieved depends on the participant ankle strength and the maximum angle limitation for the person muscle operation is different for each person.

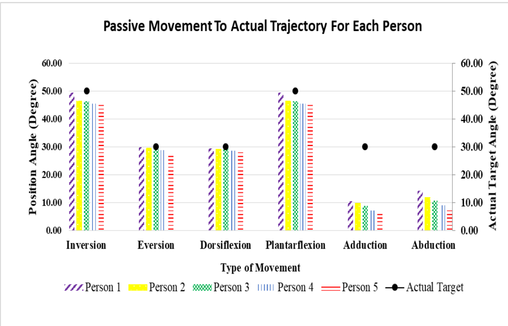

Figure 14. Passive Movement to the Actual Trajectory Collect Mean Data

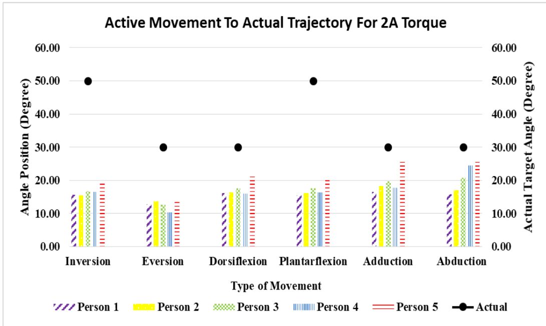

Figure 15. Active Movement to the Actual Trajectory for low Torque Stiffness Collect Mean Data

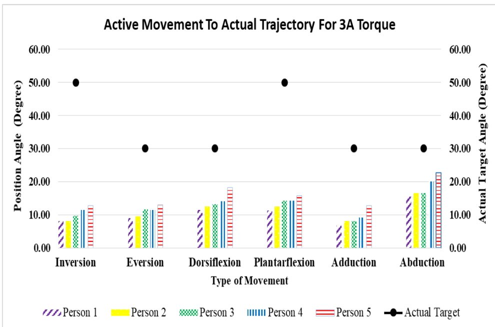

Figure 16. Active Movement to the Actual Trajectory for High Torque Stiffness Collect Mean Data

3. Conclusion

In this paper, an ankle rehabilitation system has been developed with adopted the principle of active and passive exercise for long term training. The ankle rehabilitation system has been developed with three degrees of freedom and provided a real-time to collect data for the tilt angle of the platform was established using a Gyro sensor (MPU-6050). Comparing with the current ankle rehabilitation system, this system has a Graphical User Interface which interacts with the Arduino microcontroller and Gyro sensor to record all the data accurately into Microsoft Excel. This can helps in reducing the need for human energy for manual recording data diagnosis of patients continuously for a long time and reduces the usage of paper. The whole structure is compact for the low-cost rehabilitation system and able to control three different modes of speeds for the servo motor using a smartphone as the control panel. This technology system also used Internet connectivity for the physiotherapy process that will make the patient's more

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interesting while the technology aligns with the Industrial Revolution 4.0. Based on the experiment result, the torque stiffness of the servo motor give different output result with two variable motor torque stiffness is applied. The higher torque of stiffness applied to the motor, the lower the range of motion can achieve by the subject but depends on the strength of force given. This exercise can help to increase the strength muscle force of the ankle and joint stability.

Acknowledgments

The authors would like to acknowledge the Faculty of Electronics and Computer Engineering, Universiti Teknikal Malaysia Melaka (UTeM) 76100 Melaka Malaysia for the contributions. Grant Grant is provided by Universiti Teknikal Malaysia Melaka Research Grant (PJP/2019/FKEKK(2C)/S01661).

References

[1] E. Delahunt *et al.*, "Clinical assessment of acute lateral ankle sprain injuries (ROAST): 2019 consensus statement and recommendations of the International Ankle Consortium," *Br. J. Sports Med.*, vol. 52, no. 20, pp. 1304–1310, 2018.

[2] R. A. Hauser, E. E. Dolan, H. J. Phillips, A. C. Newlin, R. E. Moore, and B. A. Woldin, "Ligament Injury and Healing : A Review of Current Clinical Diagnostics and Therapeutics, The Open Rehabilitation Journal," pp. 1–20, 2013.

[3] L. Chinn and J. Hertel, "Rehabilitation of Ankle and Foot Injuries in Athletes," *Clin. Sports Med.*, vol. 29, no. 1, pp. 157–167, 2010.

[4] T. C. Mauntel, E. A. Wikstrom, K. G. Roos, A. Djoko, T. P. Dompier, and Z. Y. Kerr, "The Epidemiology of High Ankle Sprains in National Collegiate Athletic Association Sports," *Am. J. Sports Med.*, vol. 45, no. 9, pp. 2156–2163, 2017.

[5] D. T. Fong, "Kinematics Analysis of Five Ankle Inversion Ligamentous Sprain Injury Cases in Tennis Department of Orthopaedics and Traumatology , Prince of Wales Hospital , Faculty of Medicine , The Chinese University of Hong Kong , Hong Kong , China," no. 21, pp. 402–405, 2012.

[6] J. J. Fraser, J. M. Hart, S. F. Saliba, J. S. Park, M. Tumperi, and J. Hertel, "Multisegmented ankle-foot kinematics during gait initiation in ankle sprains and chronic ankle instability," *Clin. Biomech.*, vol. 68, no. May, pp. 80–88, 2019.

[7] T. Soligard *et al.*, "Compliance with a comprehensive warm-up programme to prevent injuries in youth football," no. October, pp. 787–794, 2007.

[8] M. P. Mchugh and C. H. Cosgrave, "To stretch or not to stretch : the role of stretching in injury prevention and performance," pp. 169–181, 2010.

[9] Y. H. Tsoi and S. Q. Xie, "Impedance Control of Ankle Rehabilitation Robot," 2009.

[10] K. Gmmj, H. Hhg, D. B. R, R. Bh, and S. Paa, "Surgical versus conservative treatment for acute injuries of the lateral ligament complex of the ankle in adults (Review)," no. 3, 2007.

[11] H. J. Lee, K. B. Lim, T. H. Jung, D. Y. Kim, and K. R. Park, "Changes in balancing ability of athletes with chronic ankle instability after foot orthotics application and rehabilitation exercises," *Ann. Rehabil. Med.*, vol. 37, no. 4, pp. 523–533, 2013.

[12] W. Petersen *et al.*, "Treatment of acute ankle ligament injuries: A systematic review," *Arch. Orthop. Trauma Surg.*, vol. 133, no. 8, pp. 1129–1141, 2013.

[13] P. A. Gribble *et al.*, "Evidence review for the 2016 International Ankle Consortium consensus statement on the prevalence, impact and long-term consequences of lateral ankle sprains," *Br. J. Sports Med.*, vol. 50, no. 24, pp. 1496–1505, 2016.

[14] P. J. van der Wees, A. F. Lenssen, E. J. M. Hendriks, D. J. Stomp, J. Dekker, and R. A. de Bie, "Effectiveness of exercise therapy and manual mobilisation in acute ankle sprain and functional instability: A systematic review," *Aust. J. Physiother.*, vol. 52, no. 1, pp. 27–37, 2006.

[15] S. Guillo *et al.*, "Consensus in chronic ankle instability : Aetiology, assessment, surgical indications and place for arthroscopy," *Orthop. Traumatol. Surg. Res.*, vol. 99, no. 8, pp. S411–S419, 2013.

[16] M. Garcia, E., Jimenez, M. A., De Santos, P. G., & Armada, "The evolution of robotics research," no. March, pp. 90–103, 2007.

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[17] R. Lemoyne, T. Mastroianni, A. Hessel, and K. Nishikawa, "Ankle rehabilitation system with feedback from a smartphone wireless gyroscope platform and machine learning classification," *Proc. - 2015 IEEE 14th Int. Conf. Mach. Learn. Appl. ICMLA 2015*, pp. 406–409, 2016.

[18] R. C. Wagenaar, I. Sapir, Y. Zhang, S. Markovic, L. M. Vaina, and T. D. C. Little, "Continuous monitoring of functional activities using wearable, wireless gyroscope and accelerometer technology," in *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS*, 2011, pp. 4844–4847.

[19] J. R. Jungwon, "Reconfigurable Ankle Rehabilitation Robot for Various Exercises," vol. 22, pp. 15–33, 2006.

[20] H. I. Krebs, L. Dipietro, B. T. Volpe, and N. Hogan, "Rehabilitation Robotics : Performance-Based Progressive Robot-Assisted Therapy," pp. 7–20, 2003.

[21] Z. M., D. T.C., and X. S., "Effectiveness of robot-assisted therapy on ankle rehabilitation--a systematic review," *J. Neuroeng. Rehabil.*, vol. 10, p. 30, 2013.

[22] M. Nazrin, S. Bin, S. Aman, S. Nisha, and B. Basah, "Design and Kinematic Analysis of Parallel Robot for Ankle Rehabilitation," vol. 447, pp. 1279–1284, 2014.

[23] K. A. Shorter, G. F. Kogler, E. Loth, W. K. Durfee, and E. T. Hsiao-Wecksler, "A portable powered ankle-foot orthosis for rehabilitation," *J. Rehabil. Res. Dev.*, vol. 48, no. 4, pp. 459–472, 2011.

[24] H. Yu *et al.*, "Mechanical design of a portable knee-ankle-foot robot," *Proc. - IEEE Int. Conf. Robot. Autom.*, pp. 2183–2188, 2013.

[25] Z. Zhou, Y. Zhou, N. Wang, F. Gao, K. Wei, and Q. Wang, "On the design of a robot-assisted rehabilitation system for ankle joint with contracture and/or spasticity based on proprioceptive neuromuscular facilitation," *Proc. - IEEE Int. Conf. Robot. Autom.*, pp. 736–741, 2014.

[26] T. Yootho and J. Prinyakupt, "Design and construction the ankle movement machine for the hemiplegia patients," *2016 9th Biomed. Eng. Int. Conf.*, pp. 1–4, 2016.

[27] T. B. Palmer, K. Akehi, R. M. Thiele, D. B. Smith, A. J. Warren, and B. J. Thompson, "Dorsiflexion, plantar-flexion, and neutral ankle positions during passive resistance assessments of the posterior hip and thigh muscles," *J. Athl. Train.*, vol. 50, no. 5, pp. 467–474, 2015.

[28] S. V Dhule, V. V Shete, and S. B. Somani, "Adaptive Dorsiflexion and Plantar flexion in Active Ankle Foot Orthosis," vol. 4, no. 6, pp. 4–7, 2015.

[29] C. E. Syrseloudis, I. Z. Emiris, T. Lilas, and A. Maglara, "Design of a simple and modular 2-DOF ankle physiotherapy device relying on a hybrid serial-parallel robotic architecture," *Appl. Bionics Biomech.*, vol. 8, no. 1, pp. 101–114, 2011.

[30] A. B. Farjadian, M. Nabian, M. K. Holden, and C. Mavroidis, "Development of 2-DOF ankle rehabilitation system," *Proc. IEEE Annu. Northeast Bioeng. Conf. NEBEC*, vol. 2014-Decem, pp. 2–3, 2014.

[31] S. V. Dhule, V. V. Shete, and S. B. Somani, "Implementation of adaptive dorsiflexion and plantar flexion in active ankle foot orthosis," *Proc. - IEEE Int. Conf. Inf. Process. ICIP 2015*, pp. 714–718, 2016.

[32] C. M. Racu Cazacu, C. M. Racu Cazacu, and I. Doroftei, "Ankle rehabilitation device with two degrees of freedom and compliant joint," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 95, no. 1, 2015.

[33] Z. Lu *et al.*, "Development of an Ankle Robot MKA-III for Rehabilitation Training *," no. c, pp. 523–527, 2016.

[34] C. Wang *et al.*, "Development of an ankle rehabilitation robot for ankle training," *2015 IEEE Int. Conf. Inf. Autom. ICIA 2015 - conjunction with 2015 IEEE Int. Conf. Autom. Logist.*, no. August, pp. 94–99, 2015.

[35] Y. Wang, Z. Mei, J. Xu, and G. Zhao, "Kinematic design of a parallel ankle rehabilitation robot for sprained ankle physiotherapy," *2012 IEEE Int. Conf. Robot. Biomimetics, ROBIO 2012 - Conf. Dig.*, pp. 1643–1649, 2012.

[36] A. Petcu, M. Georgescu, and D. Tarniţă, "Actuation Systems of Active Orthoses Used for Gait Rehabilitation," *Appl. Mech. Mater.*, vol. 880, pp. 118–123, 2018.

[37] S. M. Hatem *et al.*, "Rehabilitation of Motor Function after Stroke: A Multiple Systematic Review Focused on Techniques to Stimulate Upper Extremity Recovery," *Front. Hum. Neurosci.*, vol. 10, no. September, pp. 1–22, 2016.

[38] V. Joukov, V. Bonnet, M. Karg, G. Venture, and D. Kuli, "Rhythmic Extended Kalman Filter for Gait Rehabilitation Motion Estimation and Segmentation," vol. 4320, no. c, pp. 1–12, 2017.

[39] S. Li, H. Meng, J. Xie, and C. Cheng, "Using MEMS - based inertial sensor with ankle foot orthosis for telerehabilitation and its clinical evaluation in brain injuries and total knee replacement patients," 2015.