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Design and Development of Ankle-Foot Rehabilitation Exerciser (AFRE) System Using Pneumatic Actuator

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***Abstract*—This research presents the design and development of a novel strategy for an Ankle-Foot Rehabilitation Exerciser (AFRE) system. AFRE system can be used Continuous Passive Motion (CPM) device and strength endurance training device for early stage functional rehabilitation. The designed mechanism can allow desired maximum and minimum Range of Motion (ROM) for dorsiflexion and plantar flexion (upwards and downwards stretching). This device consists of a new moveable mechanism design prototype using a new double acting Intelligent Pneumatic Actuator (IPA), embedded controller and communication protocol. The drive system consists of a nonlinear moving pneumatic actuator that controls the angle position, force and compliance for stiffness characteristic of the ankle-foot orthosis platform. In addition, the device can be configured through MATLAB via personal computer where the user can adjust the required ROM and resistance for the user in real-time. Analysis carried out during the system validation and testing through selected subjects are presented and discussed. This AFRE system is expected to substitute the traditional therapy and motorized rehabilitation device to increase the healing time of the patient specifically.**

***Index Terms*—Intelligent Pneumatic Actuator (IPA); Ankle-Foot Rehabilitation Exerciser (AFRE); Predictive Functional Control (PFC)**

I. INTRODUCTION

Nowadays, there are three types of exercises used in rehabilitation processes: passive, assisted and active [1]. In passive exercises the nurse or physiotherapy moves the joint without the patient's muscles. The second type, a medium mode is the assisted exercise, which combines the efforts of patient and physiotherapy. Active rehabilitation is the purpose full voluntary exercise motion that is performed by the person himself, with and without resistance. There has been considerable interest in developing rehabilitation devices by technology development companies, institutions and universities around the world to fully rehabilitate the affected part such as knee, ankle, hands and etc.

This research focuses on ankle rehabilitation where there are many aspects of research related have been done such as the types of devices used for rehabilitation and is focused to practical rehabilitation techniques used for ankle injury rehabilitation process [2]. The purpose of rehabilitation is to ensure ankle-leg muscles work properly and have enough muscle strength to ensure that the user is able to do more activities effectively with no pain safely.

Basically rehabilitation devices consist of three approaches which are a traditional method (manually), using machines and applying robotic. Traditional method approach uses simple devices available in clinics or homes, such as elastic bands, foam rollers and wobble boards. Machines and robotics approach use a modern research technology and complex systems devices such as Biodex Balance System, Multi-Joint Systems, Continuous Passive Motion (CPM) machine and etc., where each device has their own advantages [3]. Both of these approaches have differences in terms of function and mechanical design but have similarities such as the application of electronic and computerized control systems.

The reliability of equipment is a major factor in driving consumers to buy and use the rehabilitation devices. In recent years, most of the devices use actuator as rehabilitation instrument such as pneumatic, hydraulic, motor and etc. This paper, actuator selected only focuses on the pneumatic actuator. This is because, the rehabilitation exercises system driven by a pneumatic actuator growing in the field of mechatronics. For physical therapy, impedance control of pneumatic actuator can be integrated depending on the specific rehabilitation situations. In addition, pneumatic actuators have been used because of their high power-to-weight ratio, good compliance, ease of maintenance, cleanliness, and ability to maintain high forces without overheating [4].

Starting from 1999, [5] proposed the Rutgers ankle orthopedic rehabilitation interface. This robot is based on Stewart platform with 6 degrees of freedoms (DOF) powered by pneumatic linear actuators, they include a PC with game-like virtual reality to do the exercises that control the movement and output forces of the device. However, as the drive component, the electro-pneumatic controller is rather a high cost, requires a special air compressor, and has some acoustic noises [6]. These same researches continue work for a Stewart platform-based system for ankle tele rehabilitation [7] where the Stewart platform design allows the control of forces and torques in six DOFs and movement throughout the ankle's full range of motion (ROM). The system is enhanced using double-acting pneumatic cylinders, linear potentiometers, and a 6-DOF force sensor. Linear potentiometers are attached in parallel with each cylinder and serve as position sensors. The cylinder/potentiometer assemblies are attached at one end to a fixed platform and at the other end to a mobile platform using universal joints. The data collected by sensors can be transmitted to doctors through the network. According to the data, the physicians can guide the patient to carry out more rational rehabilitation. However, Rutgers Ankle has more degrees of freedoms than those characterized by the mobility of an ankle. In order to reduce the complexity and the control difficulty, [8] presented 3 and 4 DOFs parallel mechanisms with a central strut for ankle rehabilitation.

An ankle-foot orthosis powered by artificial pneumatic muscles proposed by [9] where a pneumatically powered ankle-foot orthosis that can be used to assist gait rehabilitation is built and human locomotors adaptation is studied. Proportional myoelectric control on a non-disabled subject indicates that the human nervous system selectively modifies muscle activation patterns to control the orthosis with practice. Preliminary data using this device is able to provide 50% of the peak plantar flexor net muscle moment and about 400% of the peak dorsiflexion net muscle moment during unassisted walking.

The four DOF robots are composed of two upper platforms and three limbs drove by four double acting pneumatic cylinders with special low-friction type proposed by [4]. This design can generate metatarsophalangeal (MTP) motion between the fore and rear foot and two rotations about the ankle joint, including the heave motion. These motions are adequate for natural foot and ankle motions. The mechanism has very simple kinematics, and allows a workspace wide enough to cover the required ROM. Additional exercises, such as heel and toe raise, that were not possible with the previous rehabilitation robot systems can be implemented. Furthermore, the simple reconfiguration of the upper platforms allows one to cover more exercises, such as proprioception and balance training. A position control method, utilizing an impedance parameter of each exercise mode, is adopted.

Rehabilitation instrument to prevent contracture of ankle using the pneumatic balloon actuator is proposed by [10] [11]. The instrument was made small, easy to put on and take off, and lightweight using a tendon driven system. A tendon drive system using a pneumatic balloon was adopted as the actuator of this instrument. It consists of a tendon and a silicone tube. Both ends of the silicone tube are closed and the tube expands like a balloon with the supply of air, which distends the silicone tube and pulls the tendon. The experiments were conducted and confirmed that the instrument could perform a suitable motion to support rehabilitation.

Joints of hip, knee and ankle for rehabilitation exercise system driven by pneumatic muscle actuator is developed by [12]. This device is passive motion or active resistance motion where the adaptive resistances torque of active movement of the hip joint is created by PMA through the adjusting of electrical current of valves. The pneumatic device is composed of air supply, control valves and joints drivers. The electrical device includes control and measure units. The control structure of the developed system is effective. It is possible for legs joints to realize smooth continuous passive motion as well as adaptive, yielding, and adjustable active resistance motion.

A study of tendon injury involves damages such as foot-drop. Injury foot-drop will prevent athletes or individuals who suffer these injuries from performing dorsiflexion due to neurological, muscle and spinal cord problem. Rehabilitation device using pneumatic bellow pump Power Harvesting Ankle-Foot Orthosis (PHAFO) energy is used to restore the ability of athletes to do dorsiflexion movement and indirectly activates the nerve axon back to work again [13]. Next, [14] continued the research which uses pneumatic Powered Portable Devices Ankle-Foot Orthosis (PPAFO) to perform ankle rehabilitation process. This device provides two types of assistance for rehabilitation of ankle flexion and dorsiflexion aid behaves when doing street style as well as 2-way of a bidirectional pneumatic rotary actuator. The tool uses portable pneumatic tools and electronic devices to provide assistance to the ankle and foot. PPFAO is also effective and provides assistance to the long-time behavior of flexible and dorsiflexion while performing speech acts walk. Help is also available on the tibia bone using these tools while performing speech acts swinging the leg and stand with static where it reduces activation in the use of the tibia bone. Data from healthy walkers demonstrated functionality, and data from an impaired walker demonstrated the ability to provide functional plantar flexor assistance. Significant evidence exists to support the use of AFOs and however the therapeutic differences among them should be further investigated [2].

Another design and development of related rehabilitation devices using a pneumatic actuator are proposed as a prototype of power-assisted Knee Ankle Foot Orthosis (KAFO) using McKibben pneumatic artificial muscle. McKibben Pneumatic Artificial Muscles is selected as the pneumatic actuator and the frame was made of aluminum. The KAFO is intended as a proof-of-concept rehabilitation device for the assessment of the conceptual design and testing of the power control system. The power assisted KAFO can be easily fitted to the user comfortably where the nut is not portable due to the tethered operation with pneumatic actuators [15]. Obviously from this research, inefficient actuator and mechanism design are the key limiting factors for portable robot design [16].

By reviewing these devices using a pneumatic actuator, there are some drawbacks and limitations of data analysis such as the effect of variable position, force and stiffness characteristics for ankle-foot rehabilitation. This challenge had motivated the research in this paper that is to propose a new Intelligent Pneumatic Actuator (IPA) which developed by [17-20] to be applied as an ankle-foot rehabilitation device. The actuator has 200 mm stroke and can give force up to 120N. KOGANEI- ZMAIR optical sensor is used where a pitch of 0.01 mm small can be detected in the position accuracy. The pneumatic system presents the next-generation actuator development with new features that provide better control, highest position and speed, force accuracy, communication ability and all-in-one mechanism for compact system design. Figure 4 shows the selected pneumatic system and its parts. As shown in the figure, the pneumatic actuator is equipped with a microcontroller board that is a Programmable System on Chip (PSoC), which acts as the brain for the system and performs the local control to suit the requirements of any related applications. Contraction and extension movements are depending on the algorithm to drive the valve using pulse width modulation (PWM) duty cycle. The pneumatic actuator is able to analyze position, force, stiffness, viscosity and etc. In addition, this research also proposes a new design and development of device architecture include controllers and communication systems through the real-time embedded system.

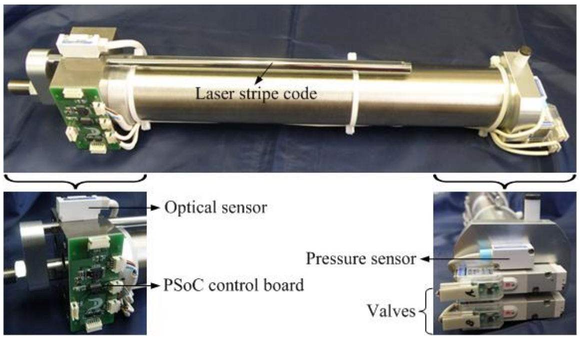


Figure 1: Intelligent Pneumatic Actuator (IPA) and its parts

The rest of this paper is organized as follows. Section II provides a prototype design and development of the AFRE. Section III presents the analysis of data collection and discussion about the system performance. A brief conclusion is given in section IV with an outline of the future work for the AFRE.

II. PROTOTYPE DESIGN AND DEVELOPMENT

Ankle-Foot Rehabilitation Exerciser (AFRE) is a combination of two systems that act as ankle rehabilitation and foot exerciser. This system can be used in general as an exercise device and not limited to patients only. There are three basic movements in the ankle-foot: dorsiflexion-plantar flexion, inversion-eversion and abduction-adduction [8]. The ankle motion mode is shown in Figure 2. The concept of the proposed ankle rehabilitation device is expected to focus on dorsiflexion-plantar flexion motion where it will substitute the traditional therapy and also will support complex movements.

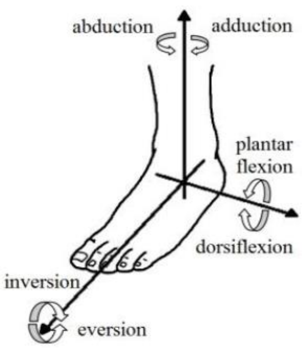


Figure 2: Movements of the ankle-foot [3]

According to the medical theory, the motions of the joints of the human body are realized through the contraction and relaxation of agonistic muscles and antagonistic muscles. The standard angle range of dorsiflexion-plantar flexion is -20 to 45 degrees [3]. Consider Figure 3 where θ denotes the angles of dorsiflexion-plantar movement, x, y are the absolute coordinate system, x', y' are the mobile coordinate system, ankle stiffness, d is a constant distance and P denotes a concentrated force because the force is part of the weight of the foot. The foot weight is not considered in the system because the user or subject is their leg when using the system, e.g. the user is sitting down. AFRE principle is developed to be user friendly where the device is easy to carry anywhere, adjustable according to user comfort and safety. The system development consists of hardware and software design.

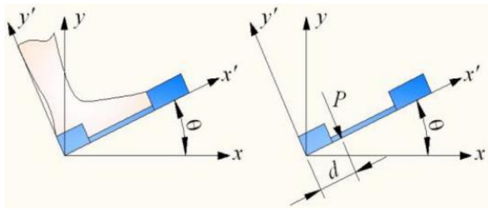


Figure 3: Position foot and angle movement [1]

Figure 4 shows the final design of real the AFRE prototype and its part followed by leg the standard design characteristics. The device is proposed to be used for both legs and is moveable in two directions depending on the user comfort. The first setting is the leg opening, while the second is the angles of dorsiflexion-plantar.

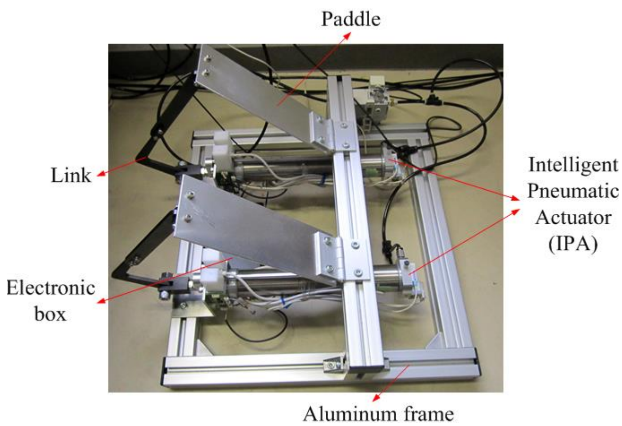


Figure 4: Real AFRE and its part

Ankle rehabilitation device consists of mechanism design (body) prototype, actuator, embedded controller and communication system. Actuator selection has been described in the introduction section where the AFRE uses a double-acting IPA. In addition, the IPA has many advantages over other actuators. Control system is the main part of the AFRE. It is consists of an electronic circuit to control the actuators and communication system. This system employs a distributed architecture where each IPA is equipped with a controller board where there are 5 connectors attached connecting to valves, pressure sensor, 2 for power supply and serial communication and 1 for re-burning programs. Each board is equipped a Cypress Semiconductor PSoC1 CY8C27443 microcontroller with 24MHz CPU, 16 kb of Flash program memory, 256 bytes SRAM data memory and configurable input/output (I/O). Having each actuator with its own controller enables multitasking and parallel processing of the control loops. This will increase the efficiency of the data processing with shorter access time. The overall system is built through the implementation of Predictive Functional Control with Observer (PFC-O) algorithm on the embedded controller boards [9], [10]. Figure 5 shows the control system containing a force control inner loop and position control outer loop to obtain the compliance control for AFRE. Stiffness parameter, ks is the resistance of an elastic ankle-foot to deflection or deformation by an applied force which is an important characteristic to the AFRE.

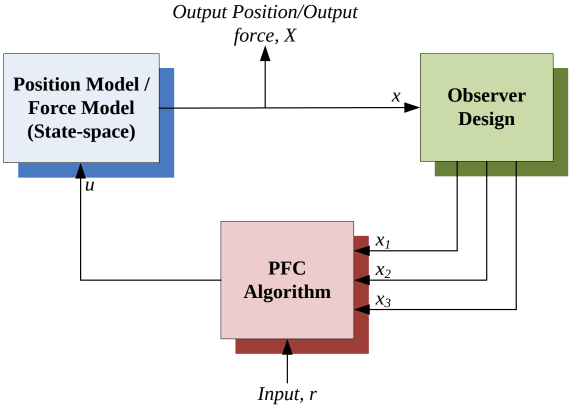


Figure 5: Block diagram for ankle rehabilitation control system

Communication links between PC and the actuators are established over an RS485 bus where a USB to UART converter is used on the PC side. Conversion between the TTL output of UARTs on the converter and the controller board to RS485 is performed using an interfacing circuit. Figure 6 shows the communication system setup using the MODBUS protocol.

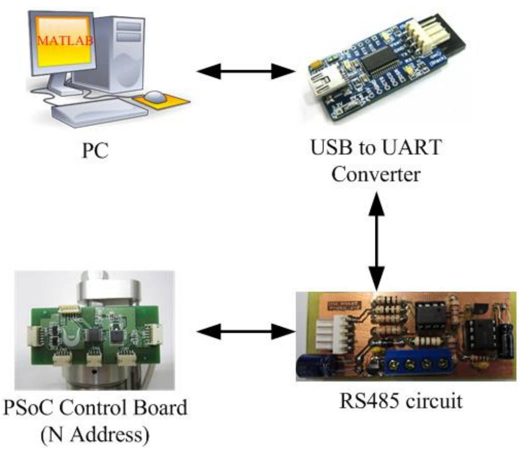


Figure 6: Communication system for ankle rehabilitation control system

III. Data Collection and Discussion

This section comprises the results of experiments in testing the capabilities of the AFRE. There are two methods of testing conducted such as the system validation testing using a measuring tool and testing of the system with randomly selected subjects.

A. System Validation Testing

This experiment setup is done to validate the position and force outputs using a measurement tool and then compared with the real-time data. There are two analyses taken from the position output and force output by using the measurement tools such as tape measure and a force gauge. The procedure is to ensure a stable system at the starting position of 50 mm and the force effect is given using force gauge on top paddle at certain times. The change in position was measured using a measuring tape. The validation with measurement tool is shown in Figure 7. Figure 8 shows the position output and force output responses with the difference stiffness parameter such as ks input of 0.5 N/mm, 1 N/mm and 2 N/mm.

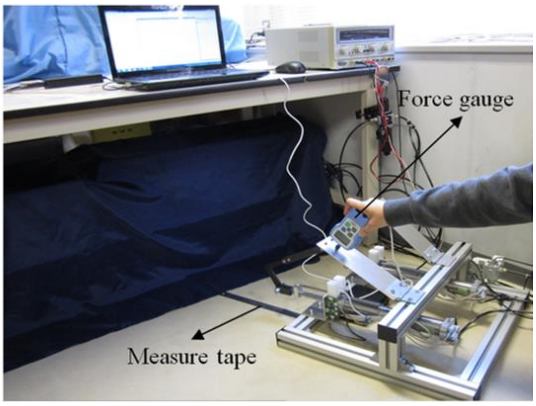


Figure 7: Validation with a measurement tool

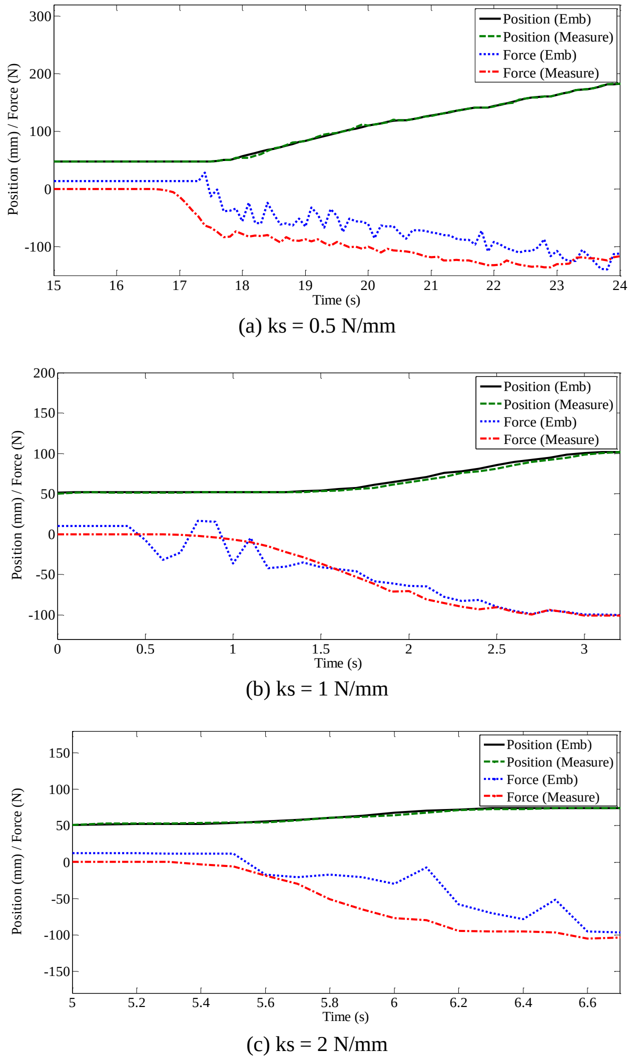


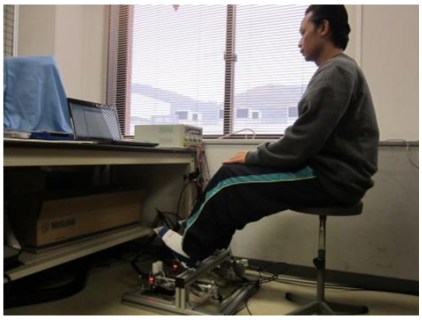
Figure 8: Comparison of measurement responses

Considering the nonlinear characteristics of the pneumatic system in this research, the position and force result from the real-time and measurement process matched closely. Therefore, this AFRE worked well as a robust system, a suitable controller with good control performance (reliability), user friendly and safe to use before taking data on each subject.

B. System Testing with Selected Subject

Testing of the system is the actual experiment on the ability of the system to work with randomly selected subjects. A total of 10 subjects consisted of students in the system integration laboratory at Okayama University were selected for this research. Each data subject is different in terms of age, body size and either left-handed or not. However, this research only shows 3 subjects selected for discussion. Figure 9 shows the real physical picture for each subject and details about the subject are as summarized in Table 1. Basically, this system can work in two-way movements where the system will semi-automatically drive to the angle of dorsiflexion-plantar flexion.

(a) Subject #1



(b) Subject #2

(c) Subject #3

Figure 9: Real physical picture for each subject

Table 1
Comparison of the Subject's Profile

Subject No. (#)	Age	Weight (Kg)	High (cm)	Left-handed (Yes/No)
1	23	52	165	Yes
2	32	69	170	No
3	21	75	186	No

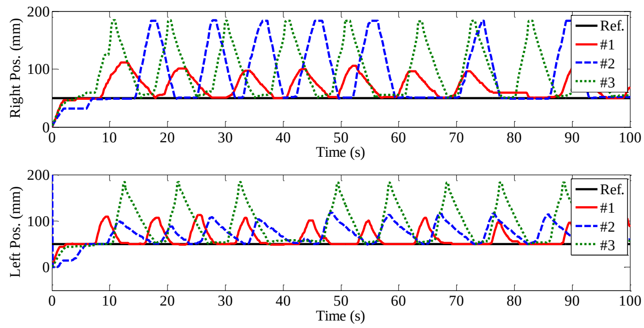
Two-way movement is controlled by the system and the effort of the user itself to improve the performance of the dorsiflexion-plantar flexion. The test is intended for the analysis of the subject ability to respond against the position and force on the system. In the initial condition, the subject will give some force on the ankle-foot where the pedal was pressed to achieve its maximum position and feels like the spring rate (stiffness characteristic). The actuator stroke will get back to the initial condition when no force is applied. In this situation, when greater stiffness setting is applied, the deflection is lesser for a given force for high stiffness, springs characteristic is hard whereby for low stiffness springs characteristic is soft. The following are the two-way movement procedure to test the dorsiflexion-plantar flexion using AFRE.

i. Insert data subject to ankle rehabilitation document.
ii. Setting data to ankle rehabilitation GUI where select the position step input response (Initial condition = 50 mm) and starting lower stiffness value (k_s = 0.5 N/mm, 1 N/mm and 2 N/mm).
iii. Put right foot on the paddle.
iv. Measure angles of heels with a paddle at 90 degrees in the initial condition.
v. Run the ankle rehabilitation system.
vi. Press the paddle until it reaches to the maximum position.
vii. Release pressure on the foot until position return to the initial condition.
viii. Repeat action in number 6 continuously until the end of the given period (100 s) and save the data.
ix. Reset the system and change the stiffness value.
x. Repeat number 2 and change to the left foot.
xi. Close the system.

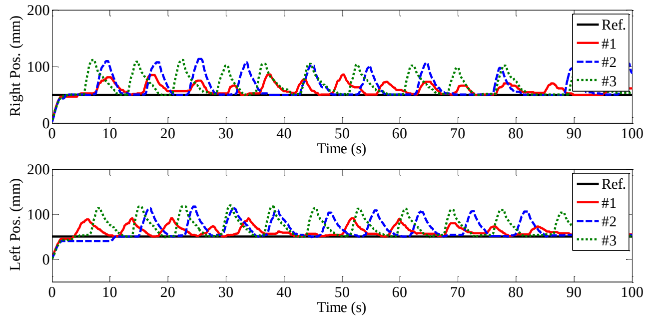
Position outputs data response are shown in Figure 10 for three differences in stiffness values, ks there are 0.5 N/mm, 1 N/mm and 2 N/mm. From the figure, lower stiffness will give higher displacement in feet movement. From measurement and calculation, the angle range of dorsiflexion-plantar flexion setting is 41.348 degree and maximum position of actuator stroke extraction is 185 mm from an initial condition of 50 mm.

All subjects gave the different results. This is because the position can be achieved depending on the strength movement of ankle-foot plantar flexion. Besides, the physical differences between each subject also gave some data information differences for analysis. For example, subject 1 is small physically and left-handed, and then the left foot had better performance than the right foot. Subject 2 is physically larger than subject 1 and is not left-handed.

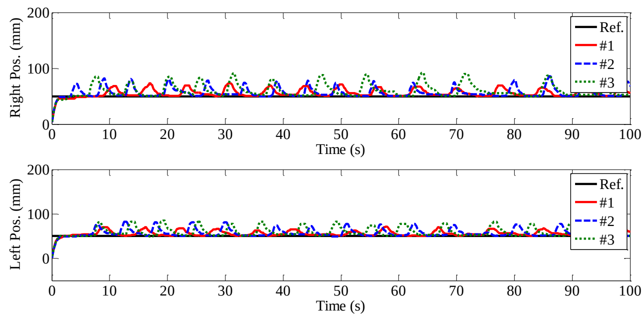
From the analysis of the responses, for small stiffness value, the right foot is able to reach a maximum position than the left foot but when the stiffness value is increased, the performance of both feet nearly shows the same results. Subject 3 is physically larger than subject 1 and 2. Subject 3 also is not left-handed. From the analysis of the responses, performance for subject 3 is better than subject 1 and 2. For small stiffness value, both feet able to reach the maximum position but when the stiffness value is increased, the performance of both feet are maintained and shows nearly the same results. The summary, subject 3 is more energetic compared to any other subject. According to the working principle and its requirements, the AFRE is successfully implemented and developed. The validation, testing and monitoring give an advantage to the user using the device for various functions especially on the performance of dorsiflexion-plantar flexion. All results obtained show that the system can be categorized as a functional device for rehabilitation and exerciser on the ankle-foot. However, the procedure for the testing not fixed but varies according to circumstances and preferences.



(a) ks = 0.5 N/mm



(b) ks = 1 N/mm



(c) ks = 2 N/mm

Figure 10: Comparison of two way movement results

IV. CONCLUSION

Ankle rehabilitation system has the potential to be marketed and used as a medical device. Ankle rehabilitation system is developed to help people including patients and athletes who suffered an ankle injury in the process of restoring the ability to perform a motion of the injured ankle-foot. The design and development of this system are appropriate for the application according to the characteristics specified. The IPA system developed with the algorithm approached enables for the data collection of position, force and stiffness characteristic. For future work, the usability evaluation of the ankle rehabilitation system can be made for the clinical study of real ankle sprain injuries patient.

ACKNOWLEDGMENT

The authors would like to thanks Universiti Teknikal Malaysia Melaka (UTeM), Faculty of Electronic and Computer Engineering (FKEKK) and Centre for Telecommunication Research and Innovation (CeTRI) for their support.

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