FABRICATION OF STEWART PLATFORM ACTUATED BY PNEUMATIC ARTIFICIAL MUSCLE FOR FOOT-ANKLE REHABILITATION

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A project report submitted in partial fulfilment of the requirements for the award of Master of Engineering (Mechanical)

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"FABRICATION OF STEWART PLATFORM ACTUATED BY PNEUMATIC ARTIFICIAL MUSCLE FOR FOOT-ANKLE REHABILITATION"** was prepared by **KRISHNAN A/L SUBRAMANIAM** has met the required standard for submission in partial fulfilment of the requirements for the award of Master of Engineering (Mechanical) at Universiti Tunku Abdul Rahman.

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ABSTRACT

Foot/Ankle injuries are amongst the most common injuries of the lower limb and almost 25,000 people are experiencing ankle injuries each day due to vigorous activities. Traditionally, ankle injuries are rehabilitated via physiotherapy, using simple equipment like elastic bands and rollers, requiring intensive efforts of therapists and patients. Currently, Stewart Platform rehabilitation devices are actuated by various methods including double acting pneumatic cylinder, hydraulic, electric motor and shape memory alloy is being used. The limitation of using these actuation methods is it, provides lower range of motions and required higher maintenances. The objective of this research is to fabricate Stewart Platform using Pneumatic Artificial Muscle, to analyse the range of motion of the foot/ankle, and to comparative study of the experiment and theoretical data. In this research study Stewart Platform with upper platform diameter 150 mm actuated by various diameters of Pneumatic Artificial Muscle (PAM) using air compressor is presented. The diameters of PAM used are 8 mm, 10 mm and 12 mm. Stewart Platform actuated by PAM with the diameter of 12 mm produced maximum platform angle of 31.73°, whereas PAM with the diameter of 10 mm and 8 mm produced maximum platform angle of 28.62° and 25.31° respectively. The developed Stewart Platform produced 31.73° range of motion (ROM) as comparing to the other researcher findings with a limited of ROM up to 20°. Performance of the prototype through experimental and theoretical results has proven relevant. This shows an improvement of the current work with the previous work.

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LIST OF SYMBOLS / ABBREVIATIONS

PAM	*Pneumatic Artificial Muscle*
SMA	*Shape Memory Alloy*
MRF	*Magneto Rheological Fluid*
ROM	*Range of Motion*
N	*Newton*

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Ankle joint is one of the significant joints in human body as it helps to maintain body balance during ambulation. In a human skeleton, human ankle joint is a very complex bony structure. Ankle sprain is a common injury and almost 25,000 people experience it each day. The number of injuries rising day by day due to vigorous activities carried out by people and this can be happened to athletes and non-athletes, children and adults. Not only due to vigorous activities but it can also happen when you simply step on an uneven surface, or step down at an angle. Ligament play important role in human ankle where it holds the ankle bones and joint in position. For all the abnormal movements-especially twisting, turning, and rolling of the foot, the ligament provides protection to the ankle joint. Since ligament is an elastic structure it has the ability goes back to their normal positions after it is stretch within their limits. Sprain occurs when ligament is forced to stretch beyond its limit. Actual tearing of the elastic fibres caused by the severe sprain [1].

Apart from ankle sprain, stroke is one of the most typical impairment which cause the patient difficult to lift their foot due to weakness in the dorsiflexion muscles. Stroke patients are most likely injured their motor fibres connected to movement. Strokes usually damage one side of the brain and affect opposite site of the body results in paralyze or difficulties in moving one side of the body. Studies shows that almost 40,000 people are suffering from strokes every year in Malaysia and 40% of the patients having moderate functional impairment which can be cured with proper rehabilitation while another 15% to 30% are facing severe disability. Figure 1 shows anatomy of human ankle [1].

1.2 Stewart Platform

Over the years, other investigation has been focused on this ankle rehabilitation therapy in order to overcome the drawback on the present ankle rehabilitation prototypes on the market. Rutgers Ankle is one of the current models established for dynamic rehabilitation recovery. A Stewart platform is a type of parallel manipulator that has six prismatic actuators. Stewart Platform moved in the six degrees of freedom in which it is possible for a freely-suspended body to move. These are the three linear movements x, y, z (lateral, longitudinal, and vertical), and the three rotations (pitch, roll, and yaw). Because of its motions, it is also called a six-axis platform or 6-DoF platform. As a part of an orthopaedic restoration system, it can stimulate revolution and transformation within its terminal.

Figure 1.1: (a) Stewart Platform (b) Ankle Rehabilitation Robots [1]

1.3 Problem Statement

Currently, Stewart Platform with Shape Memory Alloy (SMA) as actuator is being used to measure the range of motion of the foot/ankle which involves dorsiflexion, plantar flexion, inversion and eversion. The range of motion obtained from this Stewart Platform is limited and it has slow actuation and limited range of motion. In this project, the focus is to fabricate Stewart Platform with PAM to obtain high Range of Motion (ROM). The project expected to show the ROM is greater than existing.

1.4 Aims and Objectives

- To identify the Pneumatic Artificial Muscle (PAM) diameter for Stewart Platform.
- To fabricate Stewart Platform with optimize diameter of the Pneumatic Artificial Muscle (PAM)
- Comparative study of Stewart Platform actuated by PAM with SMA.

1.5 Scope of the Study

In order to achieve the above objectives, the scope of the study is as follows:

Design, test and analysis of a new prototype Stewart Platform test-rig actuates by Pneumatic Artificial Muscles were conducted. Three diameters of the PAMs namely 8 mm, 10 mm and 12 mm were used as small, medium and larger PAMs diameters. The upper platform with diameter 150 mm was designed according to ISO 7250 and ASTM standard F2004-05 (2010) to fulfil the requirement of foot/ankle length of patients. Output parameters force and range of motion are selected to investigate the performance of the Stewart Platform.

1.6 Contribution of the Study

The main contribution of this study is to increase the range of motion of the foot/ankle for stroke patients and athletes who have injured their foot/ankle. Thus, this PAM actuators prototype benefits survivor psychologically, builds endurance and may stave off future strokes and ankle injuries.

1.7 Outline of the Report

In chapter 2, extensive review of the literature has been provided along with different approach of applications in medical and non-medical. The basic characteristic of Pneumatic Artificial Muscles (PAMs) and its limitation are also discussed and methods and applications reported by several researchers in the past are reviewed.

Chapter 3 presents the materials, methods, the equipment and procedure used in this study to proceed with the experiments. The flow chart experiments, the schematics of developed Stewart Platform test-rig, system configuration and design experiments are carried out in this chapter 3. Chapter 4 covers the results and discussion. The results are the actual statement of observation, including tables and graphs. Finally chapter 5 explains the conclusion from the experimental results and analysis.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

One of the most significant joins for human is the ankle joint as it supports to maintain constancy of the body for lower limb movement. Ankle joint has a rotational motion which can be rotate in all three anatomical planes. Ankle has a high tendency to get injured since it is exerted by high pressure of the body weight during daily activities and also due to excessive movement. According to the evidence showed, ankle injuries come from sport injuries and domestic related activities. In the previous years, various types of ankle rehabilitation robots have been developed and Rutgers Ankle is well known among the ankle rehabilitation robots [2]. A few forms of actuator used for rehabilitation and range of motion obtained from the actuators used has been explained in this chapter [2].

2.2 Actuators for Foot/ankle

Equipment that changes or controls some appliance is known as an actuator. An actuator turns a control indicator into power-driven action such as an electric motor. Advancement in software technology has given rise to developments of actuators based on hydraulic, electric, thermal, pneumatic or mechanical types. In this paper we are going to discourse four types of actuators such as Shape Alloy Memory (SMA) [3], Pneumatic Driven Muscle [4] , and Hydraulic cylinder [5] which is used in ankle restoration.

2.2.1 Shape Memory Alloy (SMA)

This substance is lightweight and can be considered as solid-state substitute if compared with old fashioned actuators such as electric, hydraulic and pneumatic. Figure 2.1 represents Shape Memory Alloy. The benefit of utilizing this Shape Memory Alloy (SMA) actuator is that this alloy is famous for its noiseless actuation. In relation to mechanical-driven installation, the silent operation of SMA actuator eliminates the vibrational turbulences from other payload. In comparison with other light weight technologies, Shape Memory Alloy has the best power-to-weight ratio which means it has high potential for miniaturization. The drawback of using this Shape Memory Alloy where it has lesser energy capable compared to other actuators. SMA has a strong connection between the strain operation and fatigue life [6]. Shape Memory Alloy (SMA) have been used as an actuator in Stewart Platform as shown in Figure 2.1 [5].

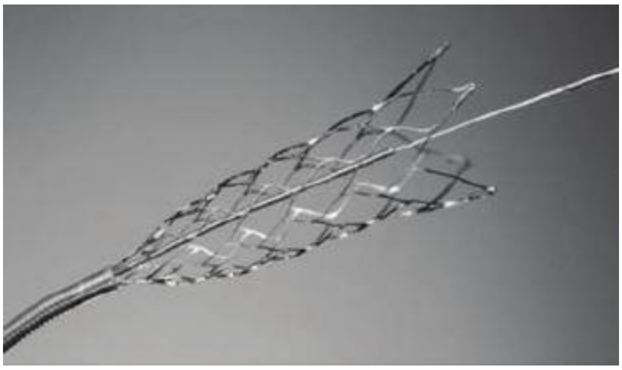


Figure 2.1: Shape Memory Alloy [5]

The benefits of using this Shape Memory Alloys (SMA) actuator are this alloy is well known for its noiseless actuation. Its silent operation eliminates the vibration to other payload that are usually $related with motor-driven positioning. Among the weightless technologies this SMA has the highest power-to-weight ratio which means it has high potential for miniaturization. The drawback of using this Shape Memory Alloy where it’s efficient is quite low compared to other actuators. Apart from this, Shape Memory Alloy (SMA) has a durable relationship between the strain operation and fatigue life [6]. Shape Memory Alloy (SMA) have been used as an actuator in Stewart Platform as shown in Figure 2.2. The ROM obtain are Plantar flexion is 20°, Dorsiflexion is 20°, Eversion is 19.87° and Inversion 19.87° [7].

Figure 2.2: Stewart Platform with Shape Memory Alloy [7]

2.2.2 Pneumatic Artificial Muscle (PAM)

Robots have become important to help and aid human specifically for older people and disabled people. Human has lenient arms and compliant joints stimulated by various muscles and this can be dangerous to humans as robots have stiffer joints. Researchers have been encouraged to study in this field and made the Pneumatic Artificial Muscle so that this problem can be solved. This PAM converts pneumatic power to pulling force and directs the movement of the mechanism. The following Figure 2.3 shows the PAM before and after contraction [8].

Figure 2.3: Pneumatic Artificial Muscle (a) before contraction (b) after contraction [8]

A thin membrane with a characteristic of lightweight is one of the important elements of PAM which helps during the replacement of a defective muscle. Another benefit of PAM in their original characteristic is when force applied on the PAM, it gives in without any changes of force in the actuation [9]. Figure 2.4 shows the PAM which is being used as an actuator. The ROM obtained are Plantar flexion is 45°, Dorsiflexion is 45°, Eversion 40° and Inversion 40° [10].

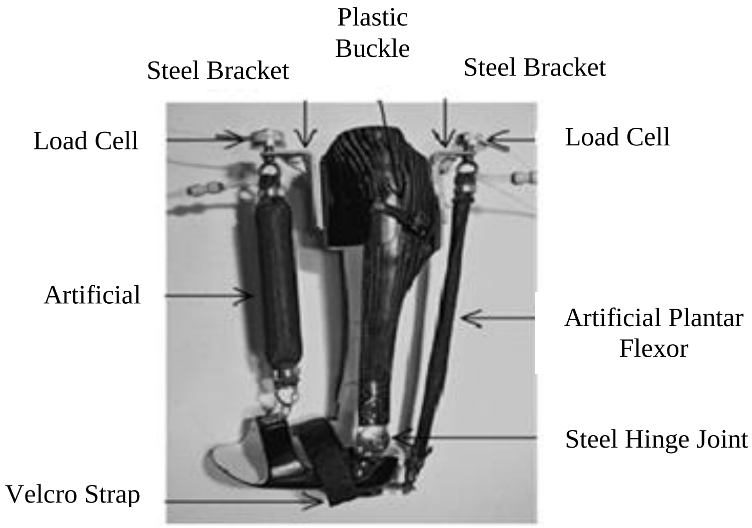


Figure 2.4: Foot and Ankle Orthotics Using Pneumatic Artificial Muscle [11]

The following Table 2.1 shows the types of braided sleeving materials which are used as sleeves in Pneumatic Artificial Muscles and its specifications.

Table 2.1 Categories of Interwoven Sleeve and its Description [12]

Braided Sleeving Materials	**Operating Temperature**	**Melting Point**	**Braid Density**
Polyester (PET)	50 °C to +150 °C	+250 °C	ca. 81%
Polyamide 6.6 (PA66)	-60 °C to +150 °C	+255 °C	ca. 85%
Polyester (PET), Tin Plated copper	-40 °C to +175 °C	+200 °C	ca. 81%
Nylon	-40 ℃ to +125℃	+250℃	ca. 81%

2.3.3 Hydraulic Actuator

Hydraulic actuator requires a cylinder or fluid motor that uses hydraulic power to enable mechanical operation. Hydraulic actuator is being used in numerous applications. Hydraulic actuator can apply a higher force like liquid are almost impossible to be compressed. Hydraulic cylinder comprises of hollow cylinder tube and a piston which can slide. Figure 2.5 shows a hydraulic actuator. High force capabilities are the main benefit to use hydraulic actuator. For an instance, even small cylinders with a high pressure can produce very high forces [13]. The design of hydraulic actuator is quite simple compared to other actuators in the current market. High maintenance is required in order to perform with higher efficiency and this is the biggest drawback of the actuator. Figure 2.6 shows hydraulic ankle foot actuator. The ROM obtained are Plantar flexion 50°, Dorsiflexion 20° [14].

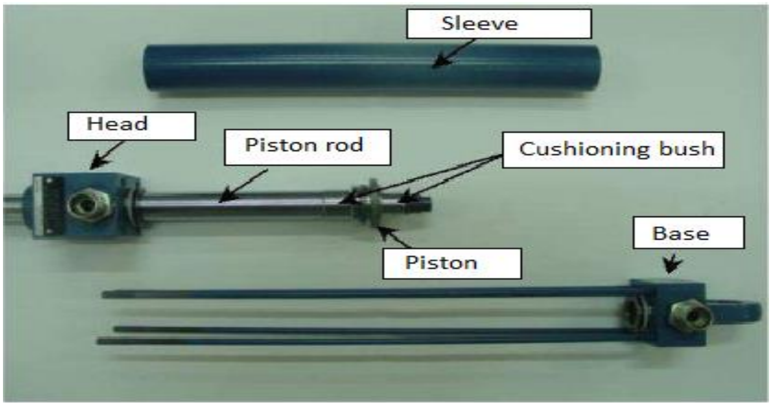


Figure 2.5: Hydraulic Actuator [13]

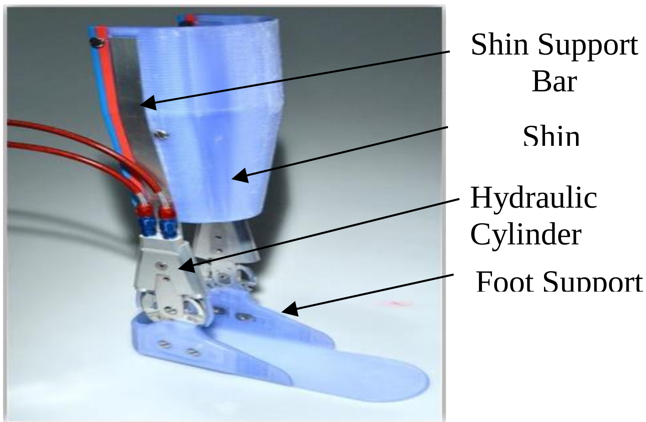


Figure 2.6: Hydraulic Ankle Foot Actuator [14]

Table 2.2 shows the characteristics of hydraulic actuators.

Table 2.2 Characteristics of Hydraulic Actuator [15]

Complexity	Moderately complex system composition
Peak Power	Very high
Position Accuracy	Mid-stroke positioning requires additional components and user support
Acceleration	Very high
Shock Loads	Explosion-proof, shock-proof and spark-proof
Utilities	Pump, power, pipes

Characteristics of hydraulic actuator are shown in Table 2.2. Hydraulic actuator has moderate complex system composition when it comes to complexity of the actuator. The peak power of the actuator is very high compare to other actuators such as pneumatic and electric actuators. Position accuracy also known as relative accuracy and absolute accuracy where for hydraulic actuator required additional components and user support for mid-stroke positioning. Hydraulic actuator has fast actuation compare to other actuators. Shock load refer as force exerted when an object suddenly accelerates and decelerates. The shock load for hydraulic actuator is explosion-proof, shock-proof and spark-proof. The utilities required for the actuator are pump, power and pipes [16].

2.3 Rehabilitation Devices for Foot/Ankle

For research and development purpose, numerous equipment was created from the transmission of the more effective systems design that can be used for ankle rehabilitation. A lot of improvements in ROM can be identified in the complexity of the devices and effectiveness for the development of rehabilitation devices. The evolutionary of the rehabilitation devices are describes as below.

2.4.1 Low Complexity Devices

Devices that do not involve any mechanicals or actuators to operate the devices are referred as low complexity devices. These devices could be uncomplicated by using elastic bands, roller foams and wobble boards as shown in Figure 2.7 (a), (b) and (c). These devices used for exercises to improve ankle strength and can be conducted both in clinic and at home. Among the low complexity devices, elastic bands are the simplest devices deliberated for muscular strengthening. Roller foam is another low complexity device which act as unstable surfaces. Better range of motion can be achieved by using this device and reduced the recovery time. Wobble board is another simple device in a circular disc shape used to improve balance and sense of motion as shown in Figure 2.7.

Figure 2.7: (a) Elastic band (b) Roller foam (c) Wobble foam [17-19]

Table 2.3 shows the limitation using Low Complexity Devices.

Table 2.3 Materials Used for Low Complexity Devices [20-23]

Low Complexity Devices	**Materials**	**Limitations**
Elastic band	Natural rubber, Synthetic Rubber, Rubber processing oil latex, Powdered pigment, Talcum powder	Problems in regulatory elastic band when it's completeley stretched.
Roller foams	Ethylene-vinyl acetate (EVA) and PVC pipe core	Slight improvement in ROM, so may not have been adequately powered to detect a difference..
Wobble board	Plastics – Low Cost and less durable Wood – Costly and more durable	Proper posturing is essential when using wobble board or else it can cause back difficulties.

These three types of low complexity devices shown in Figure 2.7, which are widely used in hospitals and therapy centres for foot/ankle rehabilitations since it is cheap and easy to use. At the same time, it has its own limitations. Materials used for low complexity devices shown in Table 2.3. Elastic bands are rubber type material. It is made of with the mixture of natural rubber, synthetic rubber, rubber processing oil latex, powder pigment and talcum powder. The limitation of elastic rubber bands are patients feel difficult in controlling the rubber band when it is fully stretched which also got high chances in further injury of the foot/ankle. Roller foams is made of Ethylene-vinyl acetate (EVA) and PVC pipe core. The limitation of using the devices are it will not have sufficiently powered to detect a significant difference since it has small improvements in range of motions. There are two type of wobble board which is plastic and wood. Wood is more stronger and expensive than plastic wobble board. The limitations are high chances of getting back problem due to inappropriate posturing [20-23].

2.4.2 Intermediate Complexity Devices

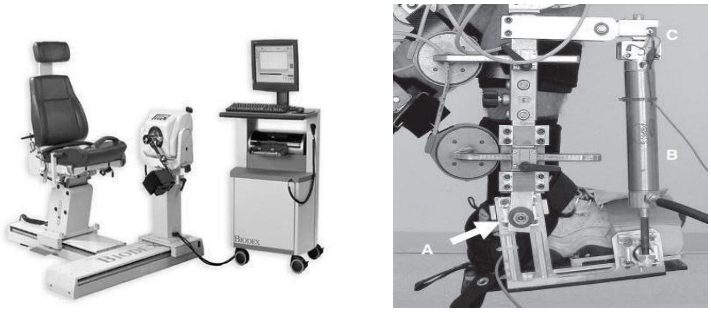
Intermediate complexity devices are referred to that electromechanical system which allows the users to stretch their muscles and tendon gently. These devices have the same movement to basic ankle movement and different ROM for each rotation that can be obtained from the devices. The main disadvantage this device is they work in a Continuous Passive Motion (CPM), while in the rehabilitation practice, the patient plays a passive role. The figure 2.8 (a), (b) and (c) below shows some of the intermediate complexity devices which are being used for ankle rehabilitation.

Figure 2.8: (a) JACE Ankle A330 CPM system (b) Optiflex Ankle CPM system (c) Kinetec Breva Ankle CPM system [24, 25]

These intermediate complexity devices help in patient recovery and being used in few rehabilitation therapies. Jace Ankle A330 CPM machine has 1 degree of freedom. The maximum range of motion of the devices are plantar flexion -40° and dorsiflexion -20°. Optiflex Ankle CPM system has 2 degree of freedom. The maximum range of motion of the device are plantar flexion -60°, dorsiflexion -40°, inversion - 40°, eversion - 20°. Kinetec Breva Ankle CPM system has 4 degree of freedom. The maximum range of motion of the device are plantar flexion -40°, dorsiflexion -30°, inversion - 25°, eversion - 25° [26-28].

2.4.3 High Complexity Devices

High complexity devices spot the maximum correlation coefficients for reliability, accuracy, validity and repeatability. These rehabilitations also help in strengthening entire lower limb. Two high complexity systems product from Biodex and Lokomat shown in Figure 2.9. More empty space is required to store this device since it is huge and a specialist is needed to operate these high complexity devices.



(a) Biodex Multi-Joint (b) Lokomat System

Figure 2.9: (a) Biodex Multi-Joint System (b) Lokomat [29, 30]

Table 2.4 shows mode of operation for Biodex Multi-Joint System which is one of the high complexity devices.

Table 2.4 Modes of Operation of Biodex Multi-Joint System [29]

Device	**Modes of Operation**
Biodex Multi-Joint System	Isokinetic Resistance Mode
	Reactive Eccentric Mode
	Passive Motion Mode
	Isometric Mode
	Isotonic Mode
	Customized Motor Control

Modes of operation of Biodex Multi-Joint system is shown in Table 2.4. Biodex Multi-Joint system have several modes of operation. The Isokinetic Resistance mode used for testing and rehabilitation where it is helpful throughout the entire range of motion. The Reactive Eccentric mode for submaximal neuromuscular re-education in the early phases of rehabilitation. The Passive Motion mode is a multi-function modality. It has a unique control properties allow for early intervention in all patients throughout all phases of rehabilitation. The Isometric mode is commonly used pre and post operatively or when pain associated with motion is a factor. The Isotonic mode allows speed to vary while providing inertia-free constant force and concentric or eccentric muscular contractions. Customized Motor Control allows for advanced specialized system control [29].

2.5 Ankle Rehabilitation Prototypes

In order to overcome the disadvantages on the current ankle rehabilitation devices in the market and also to increase the ROM, a lot of researches were conducted on the ankle rehabilitation over the years. Rutgers Ankle is one of the latest prototypes developed for both active and passive rehabilitation. It is based on a Gough-Stewart Platform which consists of 6 DOF. It even can promote rotation and translation within its workstation as a part of an orthopaedic rehabilitation system. Figure 2.10(a) shows Gough-Stewart Platform which uses visual and audio stimuli for ankle rehabilitation system. Figure 2.10(b) shows another prototype which uses 2 DOF over actuated ankle rehabilitation. These devices have the benefit of mechanical and kinematic simplicity if compared to current existing platforms. It requires smaller space to keep or facilitate and able to carry out exercises like dorsi or plantar flexion and inversion or eversion movements which is needed for ankle rehabilitation [31, 32].

Figure 2.10: (a) Gough-Stewart Platform (b) 2 DOF ankle rehabilitation robots [32, 33]

Table 2.5 shows the ankle rehabilitation exercise for the Range of Motion and strengthening mode.

Table 2.5 Ankle Rehabilitation Exercise [31]

Type of Exercise	**Exercise**	**Mode**
Range of Motion	Dorsiflexion, Plantar flexion Inversion, Eversion	Passive & Active
Strengthening	Isometric, Isotonic	Active

Ankle rehabilitation exercise is divided into range of motion exercise and strengthening exercise as shown in Table 2.5. Range of motion exercise involves dorsiflexion, plantar flexion, inversion and eversion. Strengthening involves isometric exercise and isotonic exercise [31].

2.6 Actuators used for ankle rehabilitation robots

In 2002, Terenziano Raparelli et al [34], proposed a 3-DOF robot driven by shape memory alloy. The SMA actuators are driven by Nitinol wires of a diameter of 0.15 mm. This robot has a parallel structure including a fixed plate and a moving plate. The plates are linked together by 3 SMA wires and a mechanical spring that is located in the centre of the plates. The limitation of this study is use of SMA leads to lengthy cooling times and thus consumes more time for cooling of the wire.

In 2001, Michael J.Girone et al [35], proposed a Stewart Platform structure with pneumatic actuators controlled by an electronic interface. It allows movement of the ankle though its full range of motion. The system communicates with a PC through an RS232 port. The PC will run game-like virtual reality exercises that control the movement and output forces of the device. Pneumatic actuator is used to control the movement of the Stewart Platform. The limitation of this study is its portability since it is a virtual reality exercise it needs more space and difficulties in setting up the platform.

In 2015, Bahaa I Kazem et al [36], proposed robotics system designed according to the mechanism of parallel robot and controlled by computer or microcontroller (Arduino). The purpose of this research is to provide physical therapy clinics with low cost and good reliability using electrical actuator. The limitation of this study electrical actuator easily gets over heated which can affect the performance of the actuator.

In 2012, K.S.Grewal et al [37], contribution of this paper is the design, implementation and evaluation of a Linear Quadratic Gaussian (LQG) control technique for the motion control of the pneumatic Stewart-Gough platform. The reason for the choice of pneumatics is there are very few applications using pneumatic actuation for a Stewart-Gough platform. The limitation of this study is the use of this LQG control technique can degraded the performance.

In 2010, Ye Ding et al [38], proposed a 2-DOF robot using Magneto-Rheological Fluid (MRF) as actuator. The device is developed with virtual reality interface to meet patients need for ankle and increase the range of motion of injured patient's ankle. The limitation of this study is the fluid in the actuator is subject to thickening after pro longed of use and need replacing.

In 2017, Chunbao et al [39], proposed a 3-DOF ankle rehabilitation robot using brushless DC motor as an actuator. The robot embeds force sensors and position sensor to detect the dynamic movement of the ankle. This ankle robot has high rigidity and simple design, which make the whole system more practical and stable. The limitation of this study is brushless DC motor is expensive because of its permanent magnet. It also has temperature limit on the rotor.

In 2012, Takayuki Onodera et al [40], proposed device applies a Stewart Platform mechanism to measure and assist the movements of a human ankle joint using pneumatic cylinder as actuator in six DOF. The developed device can follow frequency of 2 [Hz] and has sufficient speed for rehabilitation. The limitation of this study is it has fast actuation and not suitable for first stage patients who have just undergone surgery.

In 2015, Alaa AbuZaiter et al [41], proposed a 6-DOF 30 mm × 30 mm × 34 mm miniscale Stewart Platform using TiNiCu shape-memory-alloy (SMA). The proposed Stewart Platform possesses various advantages, such as large actuation force and high robustness with a simple mechanical structure. Each SMA actuator exerts a maximum force of 0.6 N at PWM duty cycle of 100%. The fabricated miniature Stewart Platform yields a full actuation of 12 mm in the z-axis at 55℃, with a maximum tilting angle of 30℃ in 4 s. The limitation of this study is it has long reaction time and low operation frequency. It depends on the way of heating and cooling; complicated control of displacement, because of existence of nonlinearity and hysteresis in their characteristic.

In 2009, Jody.A Saglia et al [42], proposed a 2-DOF device that allows plantar/dorsiflexion and inversion/eversion using an improved performance parallel mechanism, which makes use of actuation redundancy to eliminate singularity and greatly improves the workspace dexterity. The limitation of this study is the average failure rate of electric actuator is higher than the pneumatic actuator, due to the structural complexity of the problem, the technical requirements of the site maintenance personnel is relatively high.

In 2014, C.M.Racu, et al [43], proposed rehabilitation device using electric actuator that intend to be low cost and easy to manufacture. The system will ensure functionality but also have a small dimensions and low mass, considering the physiological dimensions of the foot and lower leg. The limitation of this study is the Vibration in servomotor.

Table 2.6 presents the limitation various actuators in the Stewart Platform. Based on the discussion on related work, a critical analysis for rehabilitation is given in the Table 2.6.

Table 2.6: Literature Table

Author	Tittle	DOF	Actuator	Objective	Limitation
Terenziano Raparelli, et al. 2002 [34]	Design of a parallel robot actuated by shape memory alloy.	3	SMA Wire	To describe the manufacture of a 3 -DOF robot driven by shape memory alloy. To explains the kinematic model, the mechanical design, and control system of the robot.	Use of SMA leads to lengthy cooling times and thus consumes more time for cooling of the wire.
Michael J.Girone, et al. 2000 [35]	The Rutgers ankle orthopedic rehabilitation interface	3	Pneumatic	To enchance rehabilitation routines by providing three types of exercise: strenghtening, stretching, and balancing.	The limitation of this platform is its portability since it's a virtual reality exercise where it is controlled by an electronic interface.

Bahaa I Kazem, et al. 2015 [36]	3-dof parallel robotics system for foot drop therapy using Arduino	3	Electrical	To provide physical therapy clinics with low cost and good realibility controlled by microcontroller (Arduino).	Electrical actuator easily gets over heated which can affect the performance of the actuator.
K.S.Grewal, et al. 2012 [37]	LQG controller design applied to a pneumatic stewart-gough platform	6	Pneumatic	The control approach for motion control of the platform is presented using a LQG which is a modern control technique. To test the robustness of the control scheme under various load condition.	Use of LQG control technique degraded the performance.
Ye Ding et al. 2010 [38]	Northeastern University Virtual Ankle and Balance Trainer	2	Magneto-Rheological Fluid (MRF)	To develop two degree of freedom (DOF) mechatronic device with a virtual reality interface to meet the needs of patients for rehabilitation.	The fluid subject to thickening after pro longed of use and need replacing.

Chunbao et al. 2017 [39]	Development of an Ankle Rehabilitation Robot for Ankle Training	3	Brushless DC motor	To design ankle rehabilitation robot which combines active and passive training together using three brushless motor to direct three rotation motions directly.	Brushless DC motor is expensive because of its permanent magnet. It also has temperature limit on the rotor.
Takayuki Onodera, et al. 2012 [40]	Performance evaluation of novel ankle foot assist device for ankle foot rehabilitation	6	Pneumatic	To investigate the accuracy of the performance of motion control of the developed device.	It has fast actuation and not suitable for first stage patients who have just undergone surgery.

Alaa AbuZaiter et al. 2015 [41]	Development of Miniature Stewart Platform Using TiNiCu Shape-Memory-Alloy Actuators	6	SMA	To fabricate miniscale Stewart Platform using TiNiCu shape-memory-alloy (SMA) actuators which is activated by passing a current through the SMA wires using a heating circuit that generates a pulse width modulation (PWM) signal.	It has long reaction time and low operation frequency.
Jody.A Saglia et al. 2009 [42]	A High Performance 2-dof Over-Actuated Parallel Mechanism for Ankle Rehabilitation	2	Electric	To design 2-DOF ankle rehabilitation robot that makes use of actuation redundancy to eliminate singularity and greatly improve the workspace dexterity.	It required high maintenance and high cost. Actuator can be overheated easily.

C.M.Racu,I Doroftei et al. 2014 [43]	Ankle rehabilitation device with two degrees of freedom and compliant joint	4	Servomotor	To propose a rehabilitation device with low cost and easy to manufacture and ensure the functionality of the devices.	Vibration can’t be avoided in servomotor.

2.7 Critical Analysis

Almost all ankle injuries will benefit from rehabilitation programs that include therapeutic exercise. Robots are used to improve patient's ankle strength and condition by using various actuators and sensors connected to the platforms. Studies showed positive treatment outcomes from the robots which are carefully tested. After facing countless challenges, dynamic characteristics and stability of ankle rehabilitation robots improve drastically, results in better actuation mechanism and safety in using those devices. I have proposed Pneumatic Artificial Muscles to be used as actuator in ankle rehabilitation device since it can provide higher range of motion, less weight and require less maintenance. Finally, there are more research being carried out on these rehabilitation devices with various actuations and the progression of more improvement can be achieved.

2.8 Summary

From the survey of existing literature, it is clearly evident that prevalence and occurrences of disorders in foot/ankle has huge impact on the activities of daily life. Besides, limited work is done to provide better range of motion (ROM) for foot/ankle. Nevertheless, due to previously mentioned drawbacks and lack of analytical details in previous literature, there is a need to develop a rehabilitation device that can be provide better ROM for patients. As an effect to this, the existing methods and application of Stewart Platform and PAM has been overviewed and comprehensive framework have been proposed to pave way and deal efficiently with existing problems for diagnosis in foot/ankle. The details of the proposed framework will be discussed in next chapter.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

Chapter 3 describes briefly the knowledge into the techniques that will be used as a part of this research to execute the characterized objectives. In addition to this, the methods used to direct the research is being discussed. Thus, the section is categorized into a few segments to enhance the comprehension on the sequence of steps used to finish this research.

3.1.1 Research Flowchart

Experimental investigation on the force developed by Pneumatic Artificial Muscle and ROM is presented in the chapter. Figure 3.1 shows the research flow chart for the experimental procedure.

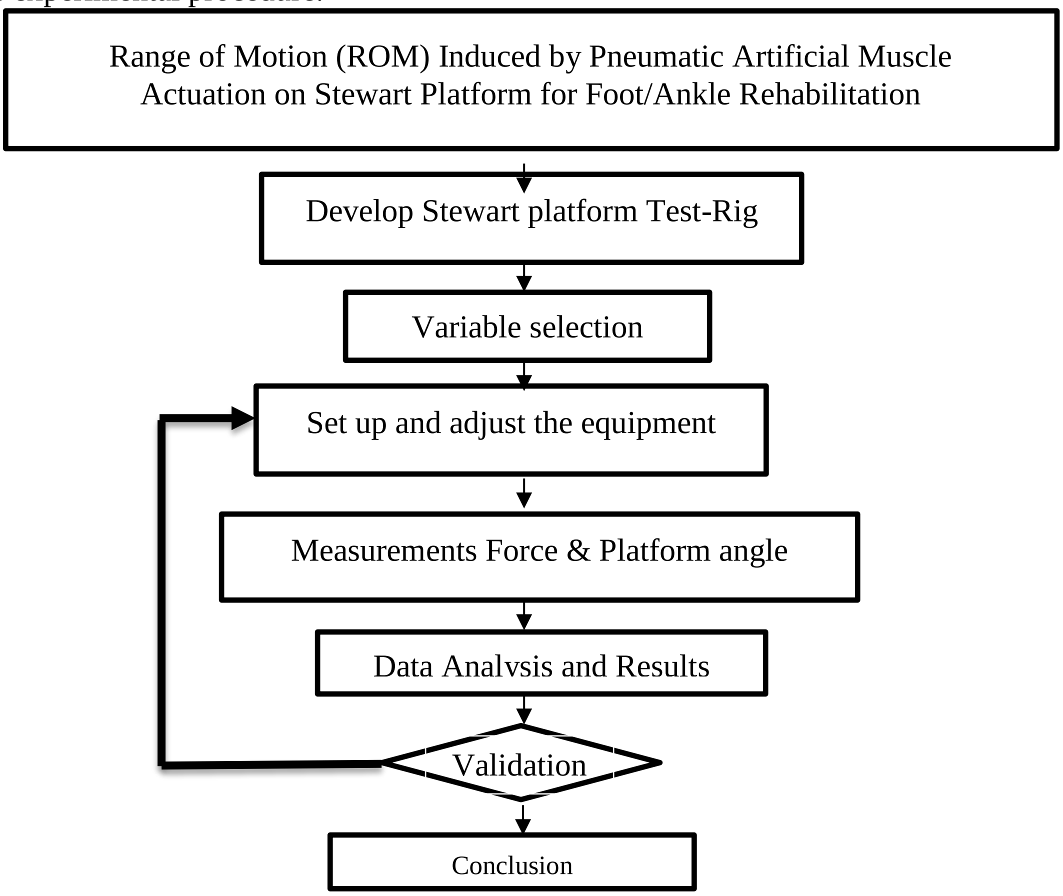


Figure 3.1: Research Flow Chart

3.1.2 Pneumatic Artificial Muscle Actuated Stewart Platform

The following section describes the prototype design of Stewart Platform with Pneumatic Artificial Muscle.

3.1.2.1 Schematic of Stewart Platform

The schematic of platform is presented in Figure 3.2 consisting of upper platform, lower platform and Delrin panel. Basically, one end of the Pneumatic Artificial Muscle is connected to upper platform and the other end is connected pneumatic fitting.

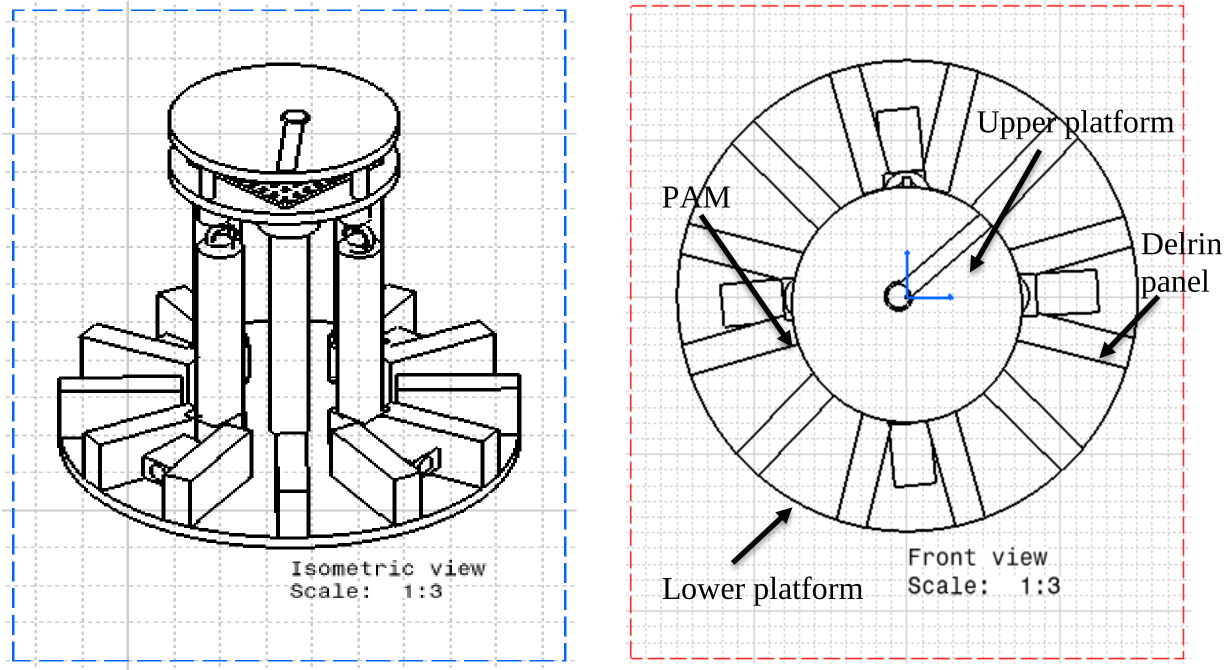


Figure 3.2: Schematic of Stewart Platform

When the Pneumatic Artificial Muscle is pressurized, the muscle will get expand and shorten which leads to the displacement of the upper platform. The upper platform will be deformed to the downward position which will create dorsi/plantar flexion movement. The gyroscope is fixed in between the upper platform to measure the top angle and force sensitive resistor (FSR-402) is fixed on top of the upper platform to measure the force applied on the platform. Figure 3.3 shows the position of upper platform before and after it is pressurized in 3D modelling.

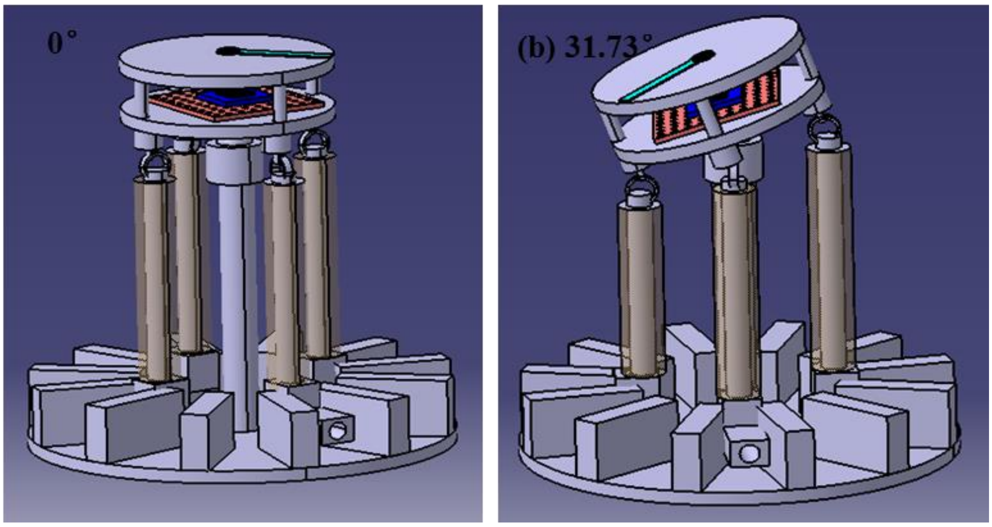


Figure 3.3: Stewart Platform Actuated by PAM (a) at 0° and (b) at 31.73°

The Pneumatic Artificial Muscle used in this experiment is enclosed with nylon braided sleeves. The PAM is pressurized from 1 bar up to 5 bars and diameter of PAM used is 12 mm. The greater the diameter of the PAM, the more the muscle can be pressurized. In order to pressurize the PAM, 12 volt dc air compressor is used. Figure 3.4 present the developed of Stewart Platform.

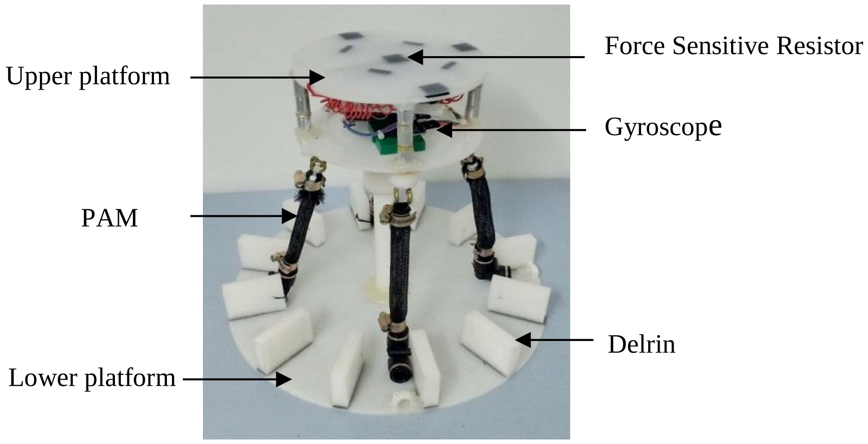


Figure 3.4: Developed Stewart Platform

3.1.3 Developed Stewart Platform Test-rig

Three Pneumatic Artificial Muscle with diameters of 8 mm, 10 mm and 12 mm were used in Stewart Platform size of 150 mm. The selection of the PAM is based on the diameter of PAM from small, medium and to larger which scientifically affect the platform angle. Smaller diameter of PAM can only withstand small amount of pressure compared to larger diameter of PAM where it can withstand larger amount of pressure which results in greater pulling force of the muscle.

The main objective is to identify the optimum platform angle deflection to promote dorsi/plantar flexion. The nominal height of each PAM is 120 mm and the longer The overall platform is made of Delrin material which is a light weight material. It has density 1.42 – 1.56 g/cm^3 and low friction compared to other materials.

3.1.4 System Configuration

Stewart Platform is actuated by Pneumatic Artificial Muscle. Figure 3.5 below shows the set-up of the developed prototype. The reading of the range of motions will be displayed when the PAM is pressurized.

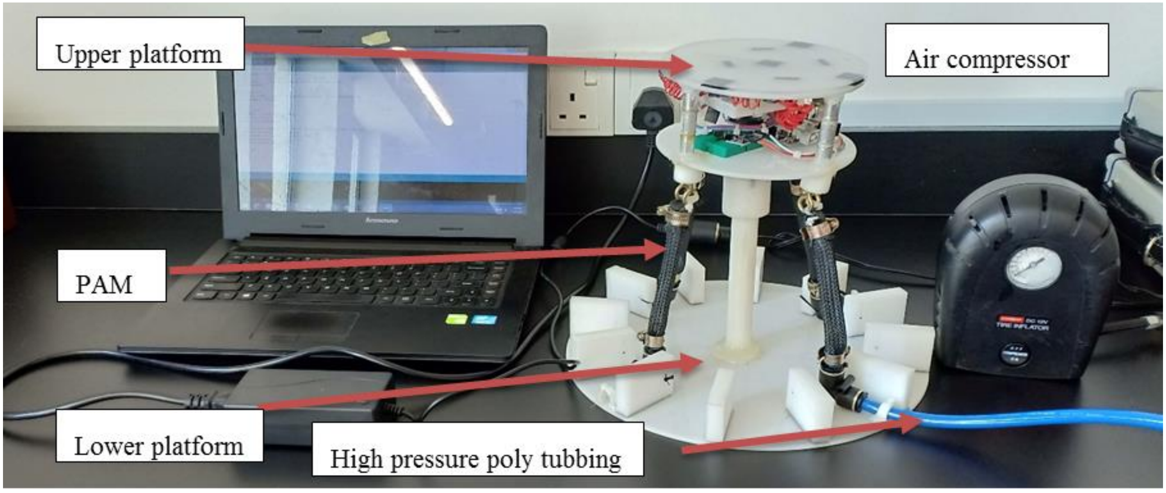


Figure 3.5: Overall Experimental Setup

Table 3.1 presents the specification of Stewart Platform actuated by PAM.

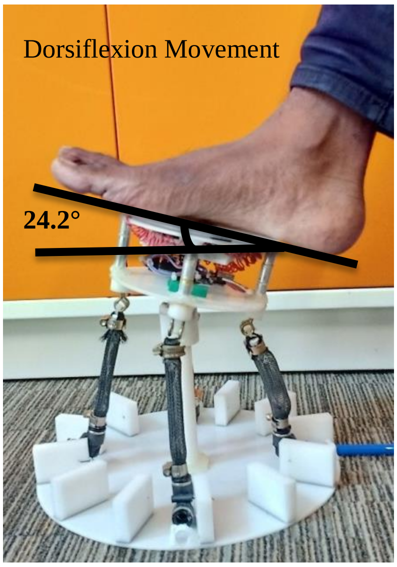
Weight	0.8 Kg
Maximum Ankle Displacement	31.73°
Dimension	
Nominal Height	190 mm
Diameter of upper platform	150 mm
Diameter of lower platform	300 mm
Length of Pneumatic Artificial Muscle	120 mm
Movable Scope	
Dorsiflexion and Plantar flexion	+ 31.73° / - 31.73°
Eversion and Inversion	+ 31.73° / - 31.73°

Table 3.1: Specification of Stewart Platform Actuated by PAM

Angle of Stewart Platform was measured using gyroscope. Dorsi and plantar flexion were measured by pressurizing from 1 bar up to 5 bars. The total height of the Stewart Platform is 190 mm and the diameter of upper platform and lower platform is 150 mm and 300 mm. This developed has a maximum ankle displacement of 31.73°.

3.1.5 Working Principle of Pneumatic Artificial Muscle Actuated Stewart Platform

The Figure 3.6 shows the Stewart Platform actuated by PAM for dorsi/plantar flexion and the identified the movable range of the Dorsiflexion and Plantar flexion 0° to 31.73° for the PAM diameter of 12 mm.



(a) Dorsiflexion Movement

(b) Plantar flexion Movement

Figure 3.6: PAM Actuated Stewart Platform for Foot/Ankle Rehabilitation
(a) Dorsiflexion Movement (b) Plantar flexion Movement

Patients during their rehabilitation phase use the Stewart Platform actuated by PAM to aid their foot/ankle motion recovery. When the PAM is pressurized, the muscle will get expand and shorten which leads to displacement of the upper platform. The upper platform will be rotated to the downward position which will create dorsiflexion or plantar flexion movement. Dorsi/plantar flexion and inversion/eversion can be achieved by the changing the platform actuation method using PAM. This can be done for the necessity of the patient's recovery.

3.1.6 Materials needed for the construction of the PAM

Table 3.2 shows materials needed and its quantity for the construction of PAM.

Table 3.2: Dimension of proposed model

No	Materials	Quantity
1	Silicone Tube (Diameter = 12mm)	2
2	Nylon Braided Sleeve (Diameter = 13mm)	2
3	Hose Clamp	4
4	Pneumatic Fittings	2
5	High Pressure Poly Tubing	1

3.1.7 Preliminary Test – Force

An experiment was carried out to select best Pneumatic Artificial Muscle. Three PAM with different diameters was taken for the force test in order to know which PAM generates greater pulling force. Diameter of the PAM used for the experiment are 8mm, 10mm and 12mm. First, all three silicone tubes are cut into length of 128mm and enclosed it with the nylon braided sleeves. Silicone tube with diameter of 8mm are enclosed with 9mm nylon braided sleeves and diameter of 10mm tube enclosed with 11mm nylon braided sleeves and finally 12mm tube are enclosed with 13mm nylon braided sleeves. All three nylon braided sleeves cut into length of 168mm. One end of the tube is fixed with pneumatic fitting while the other end is fully closed using hose clamp. Force Test was carried out to determine the pulling force of the PAM as shown in Figure 3.7.

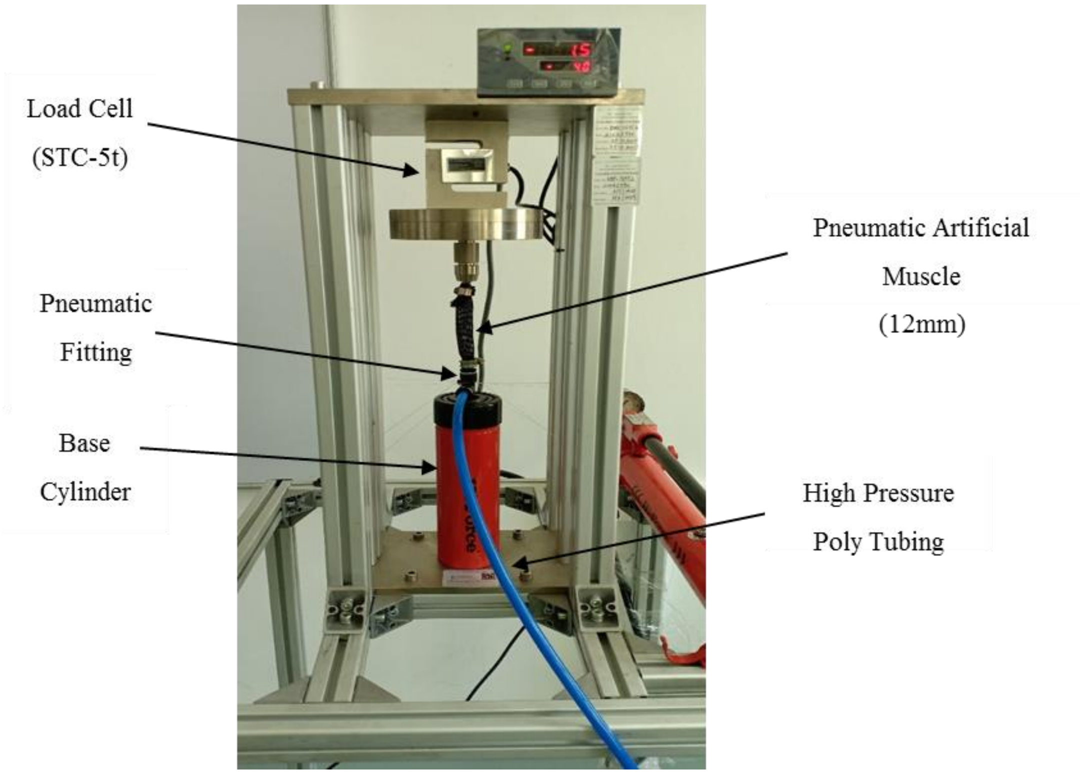


Figure 3.7: Force Test –Pneumatic Artificial Muscle

In order to measure the pulling force of the Pneumatic Artificial Muscle, the 12mm PAM is fixed in between load cell and base cylinder. High pressure poly tubing is fixed to one end of the pneumatic fitting. Air compressor is used to pressurized the PAM. The PAM is pressurized up to 5 bars and the reading was recorder.

3.1.8 Material selection for proposed design

The proposed model is made of Delrin material. Delrin material is well known for its lightness and toughness. The proposed model is designed to use at homes and clinics so weight is an important consideration. Since Delrin material is light weight so it is easy to carry and operated by the physiotherapist. It also has high strength where the proposed model does not break easily when larger force is applied on the platform. Apart from this, it has the ability to withstand high temperature. Table 3.3 shows the specification of Delrin.

Table 3.3: Specification of Delrin material [51]

Physical Properties	**Test Method**	**Units**	**Values**
Specific gravity	DIN 53479	g/cm^3	1.41
Mechanical Properties	**Test Method**	**Units**	**Values**
Tensile strength	DIN 53455	N/mm^2	70
Yield point	DIN 53455	%	40
Modulus of elasticity in tensile test	DIN 53457	N/mm^2	3100
Bending stress	DIN 53452	N/mm^2	115
Impact Strength	DIN 53453	kJ/m^2	KB
Notched impact strength	DIN 53543	kJ/m^2	> 10
Ball-indentation hardness	DIN 53456	N/mm^2	160
Stress at 1% strain 1000h	DIN 53444	N/mm^2	13
Thermal Properties	**Test Method**	**Units**	**Values**
Crystal melting range	-	^{o}C	165
Thermal conductivity	DIN 52612	W/M.K	0.31
Specific heat capacity	-	KJ^{-1} / Kg	1.5
Operating temperature continuous	-	^{o}C	-40 up to 100

3.1.9 Range of motion - Gyroscope MPU-6050

MPU6050 is a Motion Tracking Device with six Degree of Freedom (DoF) sensor which means it can provide six values as output. It is the combination of 3-axis accelerometer and 3-axis gyroscope and a digital motion processer which can provide accurate output readings. Apart from this, it also has a temperature sensor as additional features on the chip. Both the gyroscope and accelerometer embedded in the single chip. Figure 3.8 shows gyroscope MPU-6050 which is being used this prototype.

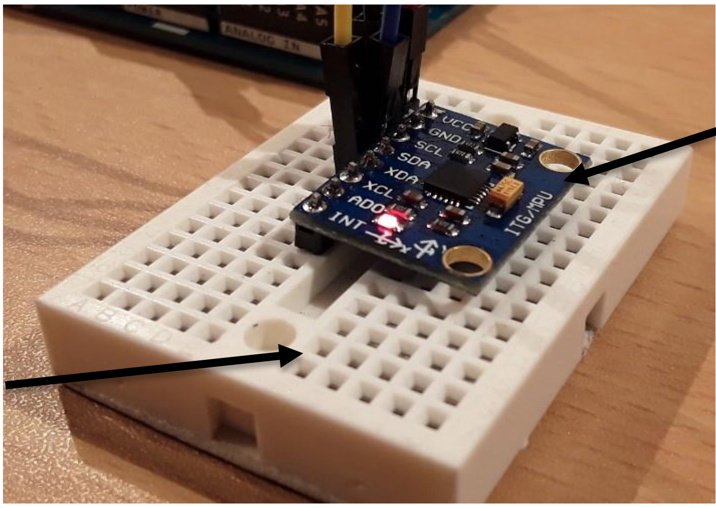


Figure 3.8: Gyroscope MPU-6050

3.1.9.1 Specification of Gyroscope MPU-6050

Table 3.4 shows specification of gyroscope MPU-6050 used to measure the range of motion.

Table 3.4: Specification of gyroscope MPU-6050 [52]

Gyroscope MPU-6050	
Power Supply	3-5V Onboard regulator
Gyroscopes range	+/- 250, 500, 1000, 2000 degree/sec
Acceleration range	+/- 2g, +/- 4g, +/- 8g, +/- 16g
Pin pitch	2.54mm
Operating current	3.6 mA
Stand by	5 µA

3.1.9.2 Working principle of gyroscope MPU-6050

MPU-6050 is a six degree of freedom (DOF) sensor module which has six output readings. It has gyroscope and accelerometer embedded in a single chip. The accelerometer in the chip work based on piezo electric effect principle. When a ball is placed in a small box where the walls of the box are made of piezo electric crystals. When the box is tilted, it follows the direction of the inclination due to the gravity force. As the ball hits the walls, small piezo electric current is produced. Inclination angle and its magnitude can be measured from the current produced.

Gyroscope which is in the small chip work based on Coriolis acceleration. For example, take a fork like structure which moves in constant forward and in backward direction and it is held in place using piezo electric crystals. Tilting of this arrangement caused the crystals to experience a force in inclination direction results of the inertia of moving fork. Current is produced by the crystals with the piezo electric effect and current is amplified.

3.1.9.3 Connection of gyroscope MPU-6050 to Arduino

Connection of Arduino to the gyroscope MPU-6050 shown in the Figure 3.9. Figure also describe which pins on the Arduino should be connected to the pins on the MPU-6050.

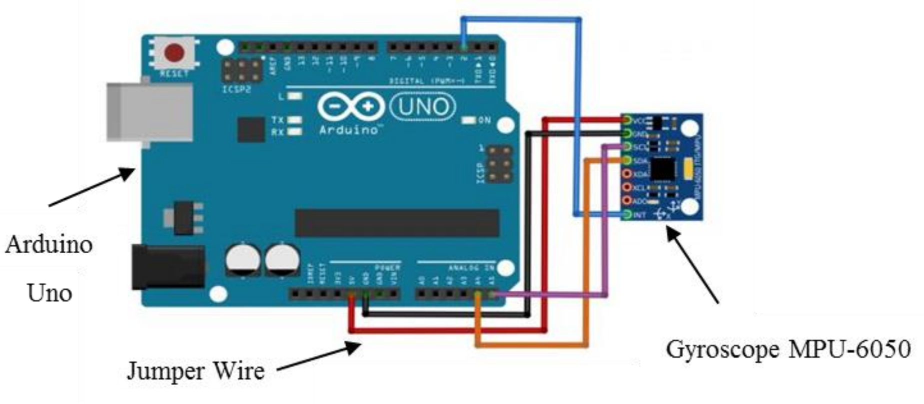


Figure 3.9: Arduino MPU-6050 connection diagram

3.1.10 Force applied - Force sensing resistor (FSR 402)

Force Sensitive Resistors (FSRs) is also known as Pressure Sensing which is used to measure pressure or force exerted on an object. It is a type of resistor when force or pressure applied, it changes the resistance. The relationship between resistance and the force applied is inversely proportional. For example, if the resistance decreases the force increases. There are few types of FSRs with different sizes and shapes. The basic FSR is in a round shape which is shown in Figure 3.10. Apart from this basic FSR there are also long strips FSRs that can sense both the pressure and position, and even x,y position and pressure using FSR matrices.

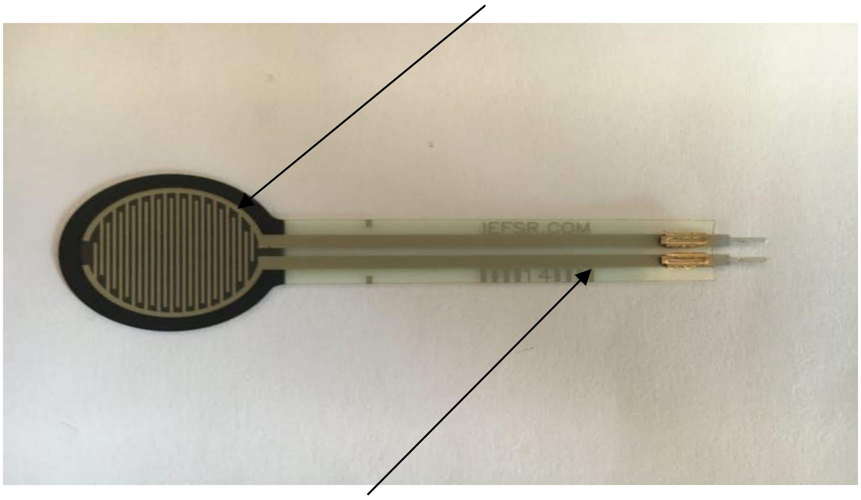


Figure 3.10: Basic Force Sensitive Resistor (FRS)

3.1.10.1 Specification of FSR 402

Table 3.5 shows the specification of Force Sensitive Resistor (FSR) 402 used to measure force applied.

Table 3.5: Specification of FSR 402 [53]

Force Sensitive Resistor (FSR) 402	
Actuation Force	0.1 Newtons
Force Sensitivity Range	0.1 - 10.02 Newtons
Force Repeatability	± 2%
Size	18.28mm diameter
Thickness Range	0.2 - 1.25 mm
Temp Operating Range (Recommended)	30 - +70 ºC

3.1.10.2 Testing of FSR 402

In order to know how the FSR works is by connecting the multi meter in resistance-measurement mode to the two tabs on the sensor and observe the changes in the resistance. Auto-ranging meter works well here since the resistance changes a lot. Figure 3.11 shows testing of FSR using multi meter.

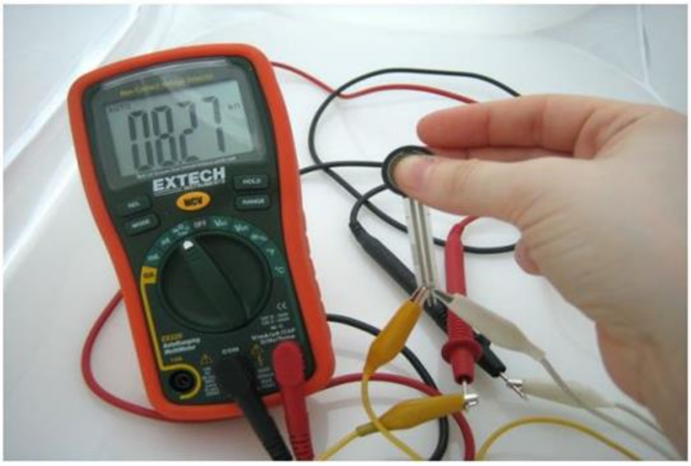


Figure 3.11: Testing of FSR using multimeter

3.1.10.3 Working principle of force sensitive resistor (FSR)

FSR consists of two substrate layers. Followed by the conductive film and the space adhesive, which includes an opening aligned with the active area. There is conductive print on substrate after the spacer layer. Conductive film experiences deformation against the substrate when external force is applied to the sensor. Conductive film comes into contact with conductive print on substrate as the air in the spacer opening is pushed through the air vent. The resistance gets lowered when the conductive ink area touches the conductive film more. As a result, more pressure is applied on the sensor. Figure 3.12 shows the substrate layer of FSR sensor.

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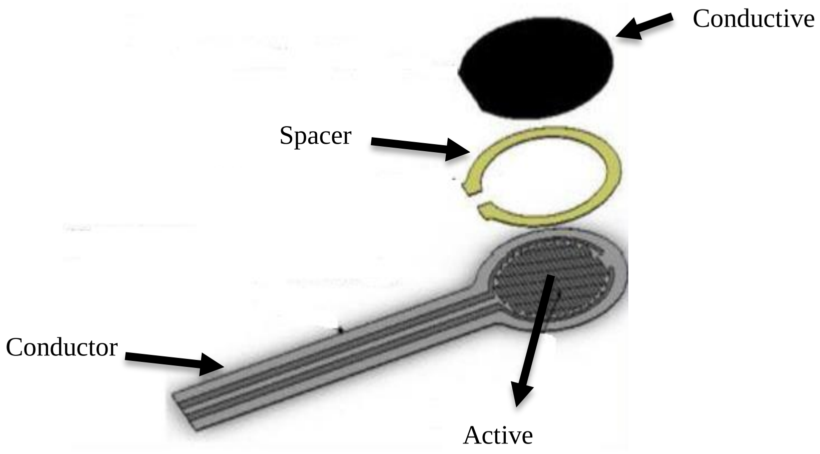

Figure 3.12: Layers of FSR 402 sensor [54]

3.1.11 Research Design

The research design of this project involves fabrication of Stewart Platform connected with smart actuator. Four Pneumatic Artificial Muscle is connected on the device to undergo dorsiflexion, plantar flexion, inversion and eversion movement. The design of this prototype is to analyze the range of motion of the ankle using gyroscope MPU6050 and measured the force applied on the upper plate using FSR 402 sensor. PAM is made of silicone tube and nylon braided sleeve. Silicone tube with diameter of 12mm is being used in PAM. The larger the diameter, more air can be supplied in the tube which results in more contraction. PAM can provide higher range of motion compared to other actuators, thus it is suitable to be used in this device.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter discusses the results of the prototype with a clear understanding view. This chapter includes the results of the range of the motion of the foot/ankle using three different diameters of Pneumatic Artificial Muscle and the preliminary test of the PAM. In addition to this, it also includes graphs that briefly explain the range of the motion of the foot/ankle and pulling force of PAM with different diameters.

4.2 Preliminary Test-Force

An experiment was carried out to select best Pneumatic Artificial Muscle. Three PAM with different diameters was taken for the force test in order to know which PAM generates greater pulling force. Diameter of the PAM used for the experiment are 8 mm, 10 mm and 12 mm. The results of the force produced by different diameters of PAM shown in Table 4.1.

Table 4.1: Force Produced by Pneumatic Artificial Muscles

Pressure Supplied (Bar)	Ø 12 mm Force (N)	Ø 10 mm Force (N)	Ø 8 mm Force (N)
1	1	1	1
2	2.5	2	1.5
3	3	2	1.5
4	3	2.5	2
5	3.5	3	2.5

Figure 4.1 shows the comparison between force produced by different diameters of Pneumatic Artificial Muscle. It is clearly showed the PAM with the diameter of 12 mm has maximum pulling force of 3.5 N when PAM is pressurized to 5 bars. The PAM with the diameter of 10 mm have a pulling force of 3.0 N. The PAM with the diameter of 8 mm have a pulling force of 2.5 N when PAM is pressurized to 5 bars. All three diameters of PAM have minimum force of 1 N when it is pressurized to 1 bar. According to PAM with the diameter of 12 mm the difference between maximum force and minimum force is 2.5 N followed by PAM with the diameter of 10 mm and 8 mm which is 2 N and 1.5 N respectively.

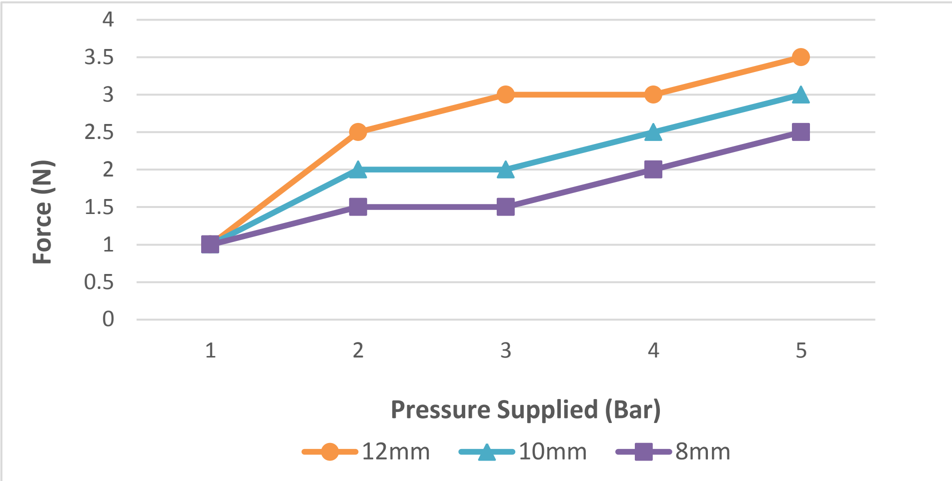

Figure 4.1: Pressure Supplied vs Force

4.3 Pneumatic Artificial Muscles with the diameter of 12 mm

Table 4.2 show the readings of range of motions which varies according to the pressure supplied. Pneumatic Artificial Muscle was pressurized from 1 bar up to 5 bars.

Table 4.2: Range of Motion of Foot/Ankle

Pressure supplied (Bar)	Range of Motion of Foot/Ankle		
	Without Load (Degree)	Patient A - Child (Degree)	Patient B - Adult (Degree)
1	2.67	2.27	2.15
1.5	4.13	3.2	3.04
2	8.03	7.89	6.27
2.5	12.96	11.77	9.8
3	15.88	14.71	12.9
3.5	19.62	18.69	15.81
4	24.37	22.49	18.46
4.5	28.13	26.22	21.63
5	31.73	28.84	24.2

Figure 4.2 shows the range of motion of the Stewart Platform without any load applied on the platform. Based on the graph above, it is clearly seen that the maximum range of motion of the platform is 31.73° when the Pneumatic Artificial Muscles is pressurized to 5 bars. The minimum range of motion obtained is 2.67° when the PAM is pressurized to 1 bar. The difference between maximum range of motion and minimum range of motion is 29.06°. The experiment was repeated several times and the average value was taken to obtain more accurate readings.

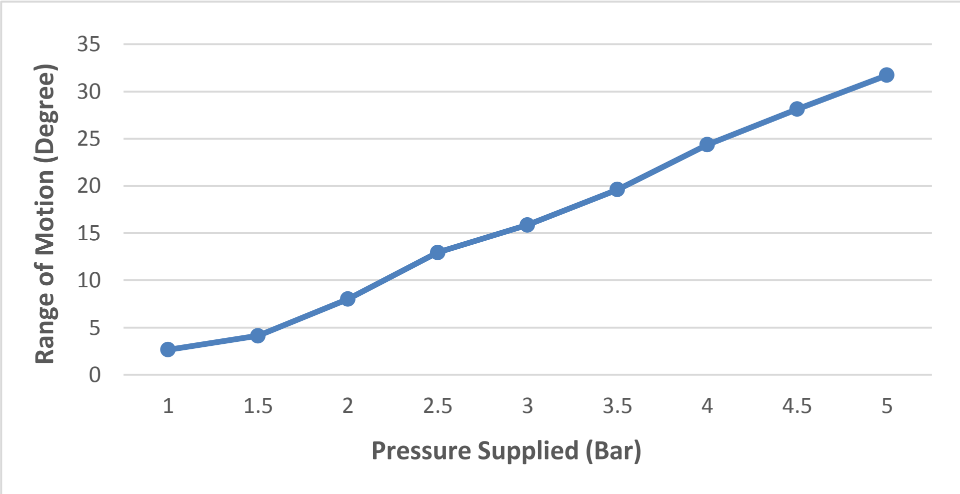

Figure 4.2: Range of Motion vs Pressure Supplied (Without Load)

Figure 4.3 shows the range of motion of the foot/ankle when a foot of Patient A with the weight of 78 N is placed on the platform. The maximum range of motion obtained is 28.84° and the minimum range of motion obtained is 2.27°. The difference between maximum and minimum range of motion is 26.57°. When the Pneumatic Artificial Muscle is pressurized from 1 bar up to 1.5 bars there is only slight increase in the range of motion. The range of motion increase drastically as the pressure supplied increases.

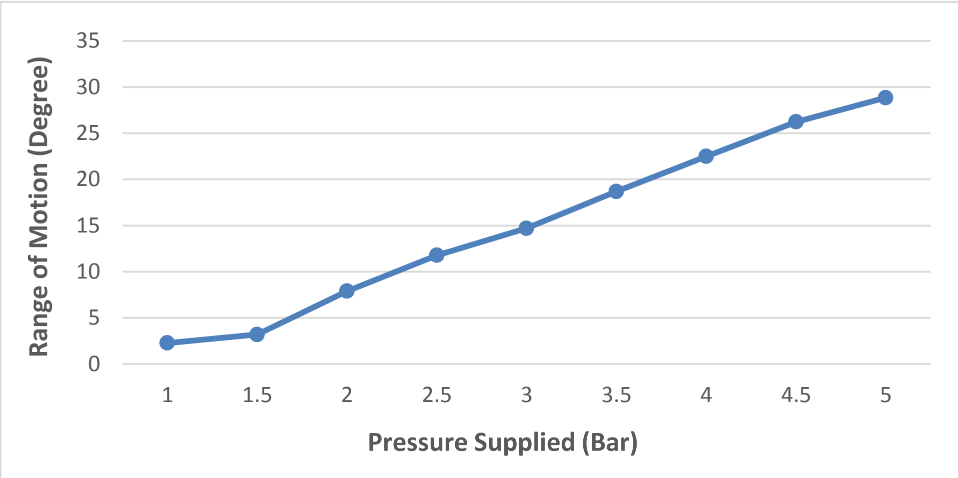

Figure 4.3: Range of Motion vs Pressure Supplied (Child)

Figure 4.4 shows the range of motion of the foot/ankle when the foot of Patient B with a weight of 147 N is placed on the platform. According to the graph, the maximum range of motion of the platform is 24.20° when the Pneumatic Artificial Muscles is pressurized to 5 bars. The minimum range of motion obtained is 2.15° when the PAM is pressurized to 1 bar. The difference between maximum and minimum range of motion is 22.05°. The experiment was repeated several times and the average value was taken to obtain more accurate readings.

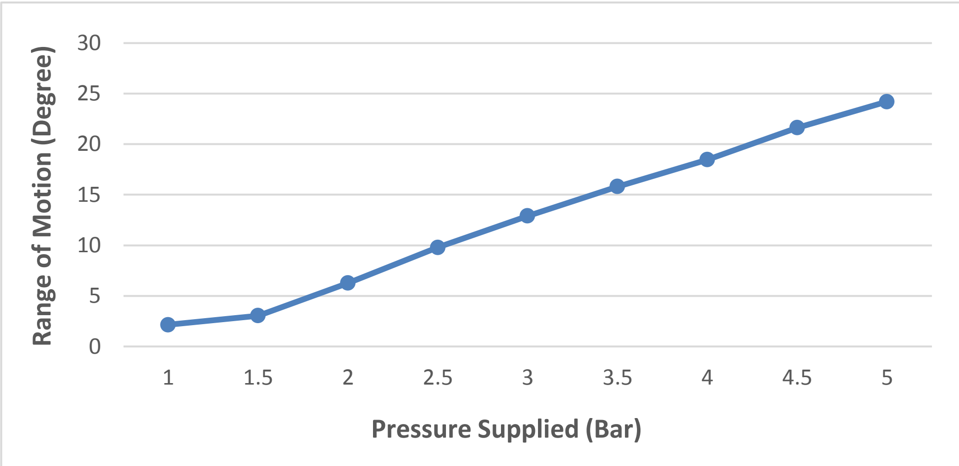

Figure 4.4: Range of Motion vs Pressure Supplied (Adult)

4.4 Pneumatic Artificial Muscle with the diameter of 10 mm

Pneumatic Artificial Muscle with the diameter of 10 mm is used and the range of motion obtained was recorded as shown in Table 4.3. The PAM is pressurized from 1 bar up to 5 bars.

Table 4.3: Range of Motion of Foot/Ankle

Pressure supplied (Bar)	Range of Motion of Foot/Ankle		
	Without Load (Degree)	Patient A - Child (Degree)	Patient B - Adult (Degree)
1	2.43	2.06	1.79
1.5	3.82	2.83	2.55
2	6.73	5.89	4.91
2.5	10.96	9.77	8.63
3	14.88	13.01	11.90
3.5	18.22	17.69	14.81
4	22.34	20.45	16.48
4.5	25.21	23.24	19.60
5	28.62	25.76	22.17

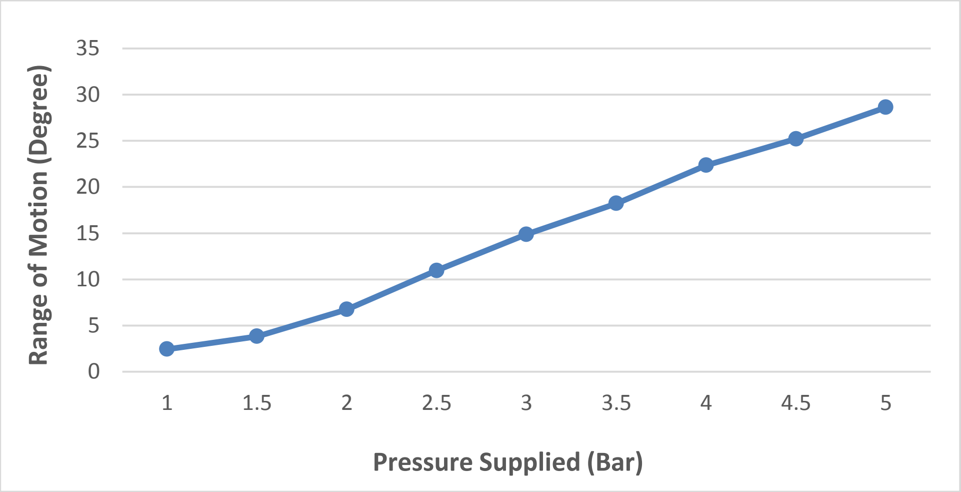

Figure 4.5: Range of Motion vs Pressure Supplied (Without load)

The above Figure 4.5 shows the range of motion of Stewart Platform without any load applied on the platform. When Pneumatic Artificial Muscle is pressurized to 1 bar and the range of motion obtained is 2.43° and it slightly increase to 3.82° when pressurized to 1.5 bars. As the pressure supplied increases the range of motion increases as well. The maximum range of motion obtained when it is pressurized to 5 bars is 28.62° where it has the difference of 26.19° between maximum and minimum range of motions.

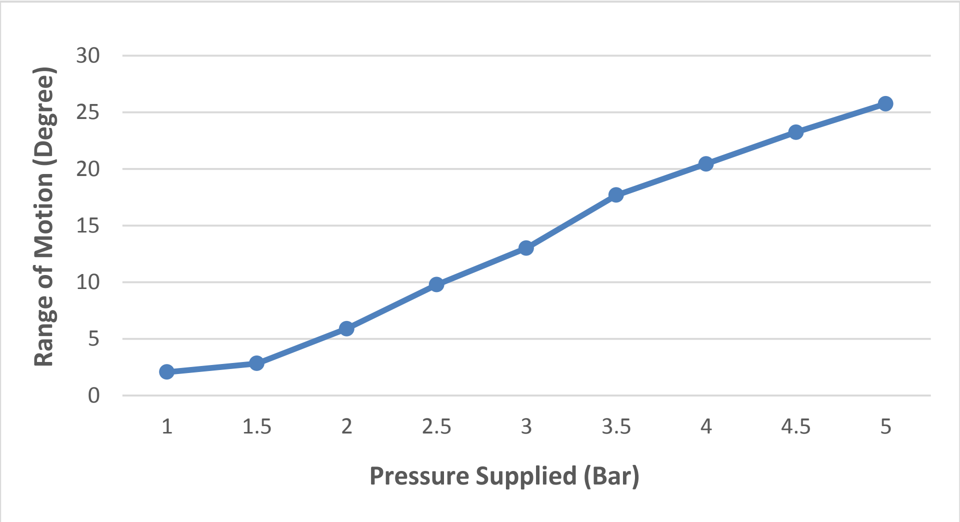

Figure 4.6: Range of Motion vs Pressure Supplied (Child)

Figure 4.6 shows the range of motion of the foot/ankle when a foot of Patient A with a weight of 78 N is placed on the platform. Based on the graph above, it is clearly seen that the maximum range of motion of the platform is 25.75° when the Pneumatic Artificial Muscles is pressurized to 5 bars. The minimum range of motion obtained is 2.06° when the PAM is pressurized to 1 bar. In addition to this, from the graph it briefs that the pressure supplied to the PAM is directly proportional to the range of motion of the foot/ankle. The difference between maximum and minimum range of motion is 23.70°.

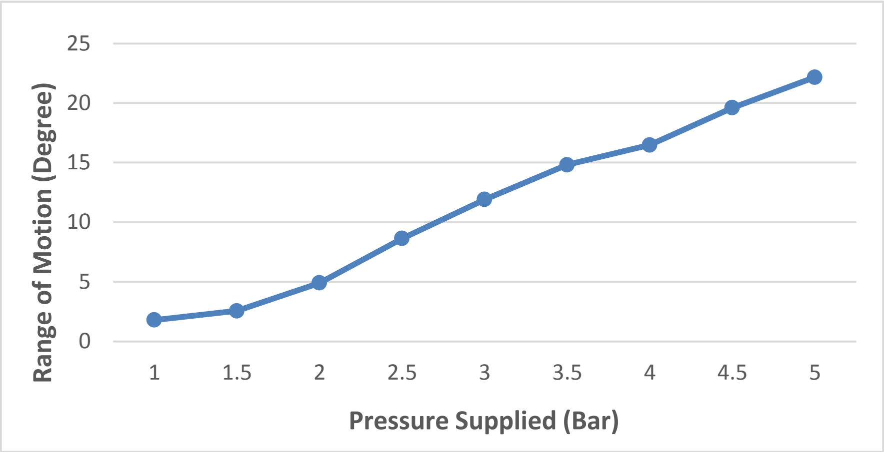

Figure 4.7: Range of Motion vs Pressure Supplied (Adult)

Figure 4.7 shows the range of motion of the foot/ankle when a foot of Patient B with a weight of 147 N is placed on the platform. Based on the graph above, it is clearly seen that the maximum range of motion of the platform is 22.17° when the Pneumatic Artificial Muscles is pressurized to 5 bars. The minimum range of motion obtained is 1.79° when the PAM is pressurized to 1 bar. The difference between maximum and minimum range of motion decreases as the smaller diameter of PAM is used.

4.5 Pneumatic Artificial Muscle with the diameter of 8 mm

Pneumatic Artificial Muscle with the diameter of 8 mm is fabricated in the Stewart Platform and the changes in the range of motion were recorded as shown in Table 4.4.

Table 4.4: Range of Motion of Foot/Ankle

Pressure supplied (Bar)	Range of Motion of Foot/Ankle		
	Without Load (Degree)	Patient A - Child (Degree)	Patient B - Adult (Degree)
1	2.21	1.81	1.55
1.5	3.66	2.53	2.27
2	5.11	4.79	4.11
2.5	9.26	8.31	7.12
3	13.56	12.32	10.31
3.5	17.24	16.72	13.43
4	21.63	19.11	15.54
4.5	23.14	21.21	18.01
5	25.31	23.10	20.88

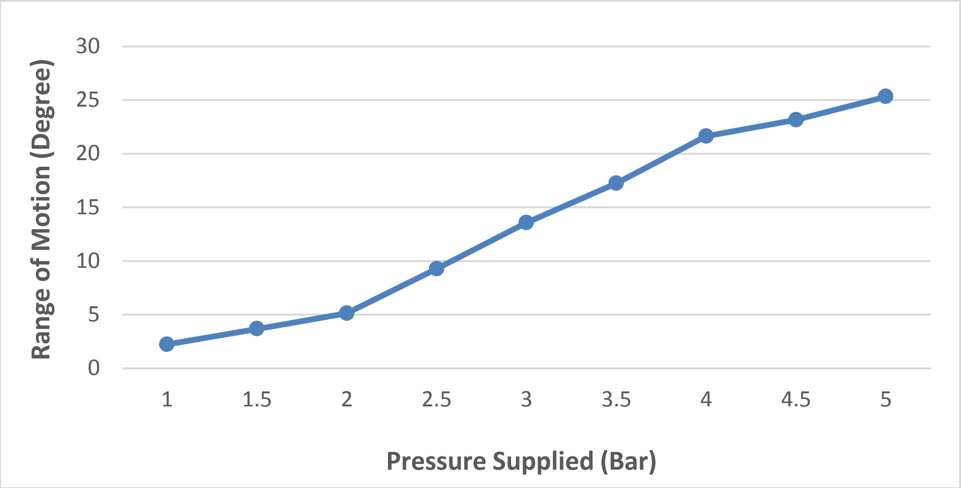

Figure 4.8: Range of Motion vs Pressure Supplied (Without Load)

Figure 4.8 shows the range of motion of Stewart Platform without any load applied on it. The maximum range of motion obtained is 25.31° and the minimum range of motion is 2.21°. The difference between maximum and minimum range of motion 23.1°. The Pneumatic Artificial Muscle is pressurized from 1 bar up to 5 bars. The experiment was repeated several times and the average value was taken to obtain more accurate readings.

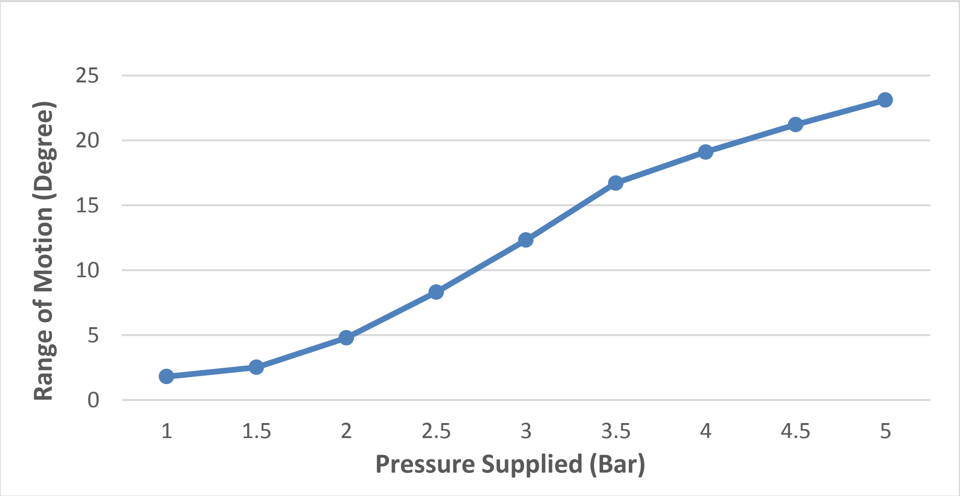

Figure 4.9: Range of Motion vs Pressure Supplied (Child)

Figure 4.9 shows the range of motion of the foot/ankle when a foot of Patient A with a weight of 78 N is placed on the platform. Based on the graph above, it is clearly seen that the maximum range of motion of the platform is 23.10° when the Pneumatic Artificial Muscles is pressurized to 5 bars. The minimum range of motion obtained is 1.81° when the PAM is pressurized to 1 bar. The different between maximum and minimum range of motion is 21.29°. As the pressure supplied increases, the range of motion increases as well.

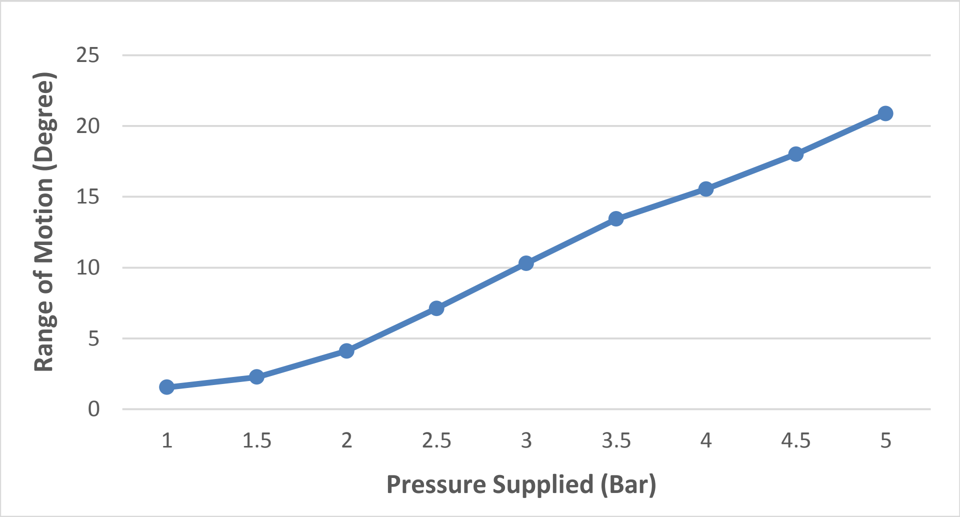

Figure 4.10: Range of Motion vs Pressure Supplied (Adult)

Figure 4.10 shows the range of motion of the foot/ankle when a foot of Patient B with a weight of 147 N is placed on the platform. Based on the graph above, it is clearly seen that the maximum range of motion of the platform is 20.88° when the Pneumatic Artificial Muscles is pressurized to 5 bars. The minimum range of motion obtained is 1.55° when the PAM is pressurized to 1 bar. The difference between maximum and minimum range of motion is 19.33°.

4.6 Comparison of Range of Motion (Without Load)

Figure 4.11 presents the comparative study of Pneumatic Artificial Muscle with different diameters which is 8 mm, 10 mm and 12 mm without any load applied on the platform.

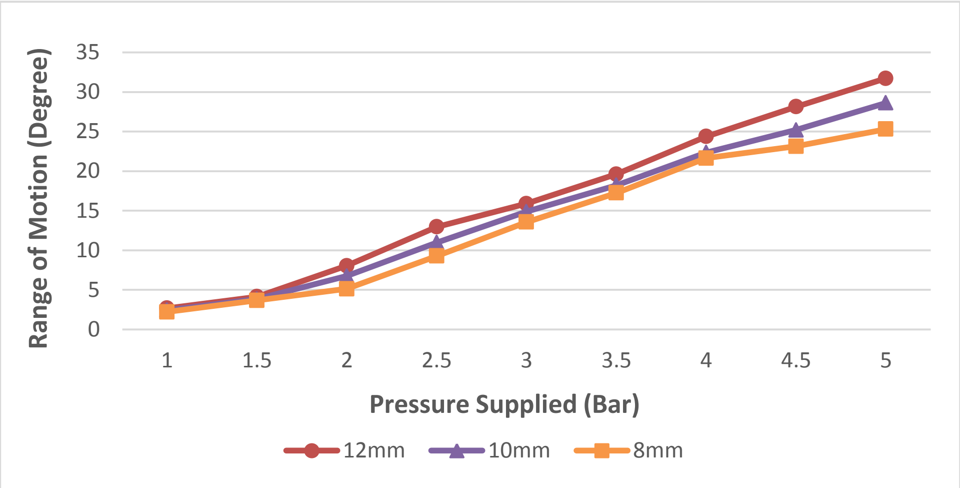

Figure 4.11: Platform Angle with Different Diameters of PAMs

Figure 4.11 shows Pneumatic Artificial Muscle with the diameter of 8 mm has minimum range of motion of 2.21° and the maximum range of motion of 25.31°. The difference between minimum and maximum range of motion of the platform is 23.1°. PAM with the diameter of 10 mm obtained minimum range of motion of 2.43° and maximum range of motion of 25.31°. The difference between maximum and minimum range of motion is 22.88°. There is a slight increase in range of motion as the diameter increases. When 12 mm PAM is used the maximum and minimum range of motion obtained is 31.73° and 2.67° respectively. The difference between maximum and minimum range of motion is 29.06°.

4.7 Comparison of Range of Motion (Patient A)

Figure 4.12 present the different diameters of Pneumatic Artificial Muscle which s 8 mm, 10 mm and 12 mm is being used to compare the range of motion when foot/ankle of Patient A is applied on the platform.

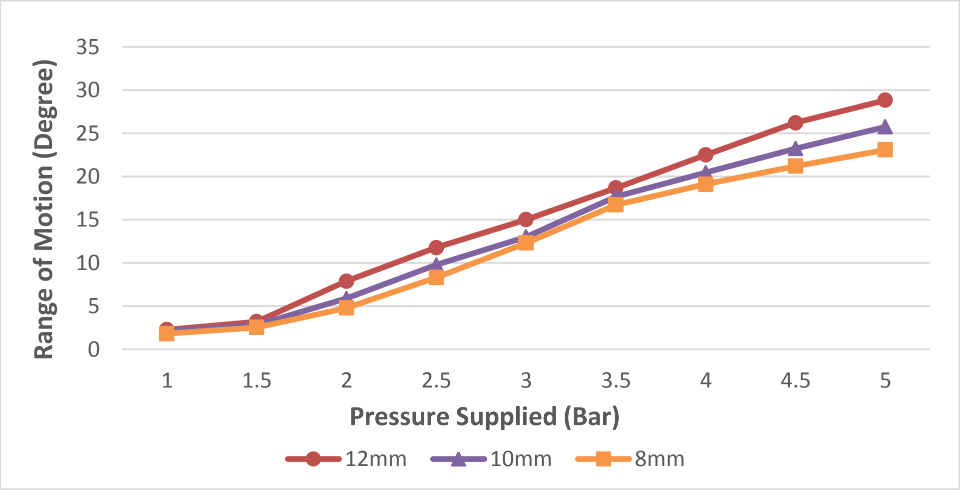

Figure 4.12: Platform Angle with Different Diameters of PAMs

Figure 4.12 shows the maximum angle of the platform when 8 mm of Pneumatic Artificial Muscle used is 23.10° and the range of motion further increases to 25.76° when 10 mm diameter of PAM is used. There is an increase of 2.66° in range of motion. When 12 mm diameter of PAM is used the maximum range of motion obtained is 28.84° which is in increase of 5.74° compared to maximum range of motion obtained by 8 mm diameter of PAM.

4.8 Comparison of Range of Motion (Patient B)

Figure 4.13 present the comparisons of range of motion when foot/ankle of Patient B is applied on the platform by using different size of Pneumatic Artificial Muscle which is 8mm, 10mm and 12mm was plotted.

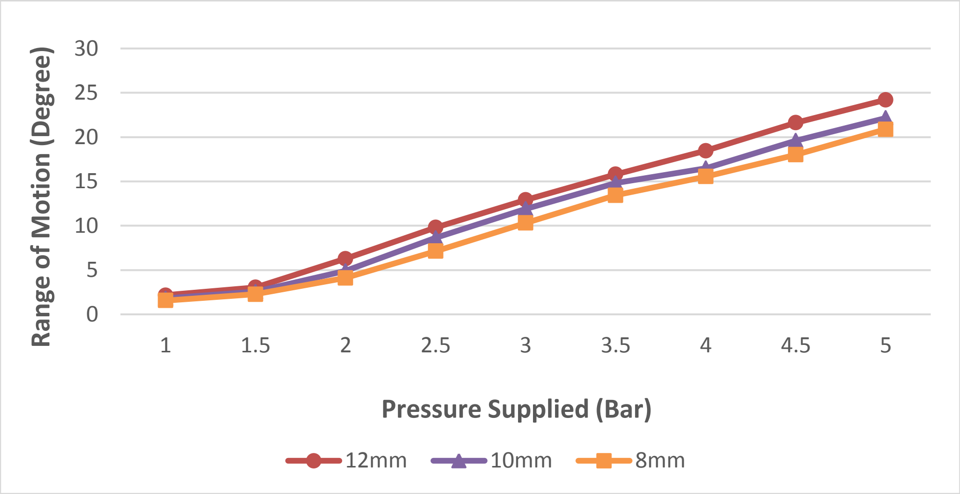

Figure 4.13: Platform Angle with Different Diameters of PAMs

Figure 4.13 shows when 8 mm diameter of Pneumatic Artificial Muscle is used the minimum range of motion is 1.55° and the maximum range of motion is 20.88°. The maximum range of motion increases to 22.17° when 10 mm diameter of PAM is used and there is increase of 1.29° in range of motion. PAM with 12 mm further increases the maximum range of motion to 24.20° which is increase in 3.32° compared to maximum range of motion of 8 mm. As the bar increases, the range of motion increases drastically.

4.9 Performance of Stewart Platform Prototype

The performance of Stewart of the 150 mm Stewart Platform actuated by 12 mm Pneumatic Artificial Muscle was tested on foot/ankle of patient A and patient B as shown in Figure 4.14 (a) and (b).

(a) (b)

Figure 4.14: Stewart Platform Actuated by 12 mm PAMs
(a): Patient A (dorsiflexion) and (b): Patient B (dorsiflexion)

Table 4.5 present the platform angle using patients to measure the dorsiflexion movement on two patients with Stewart Platform subjected to maximum pressure of 5 bars.

Table 4.5: Platform Angle: dorsiflexion movement

No	Patients	Dorsiflexion (degree)
1	A	31.73°
2	B	24.2°

Foot/ankle of patient A applied on the platform and the platform angle obtained is 31.73° and patient B obtained a range of motion of 24.2° for dorsiflexion movement when PAM is pressurized upto 5 bars.

4.10 Comparative Analysis

The developed Stewart Platform actuated by Pneumatic Artificial Muscle was proved to have foot/ankle movement suitable for rehabilitation of foot/ankle with increase range of motion (ROM). Whereas Stewart Platforms actuated by Shape Memory Alloy (SMA) lead to very slow actuation of the platform. This can cause a negative impact on the foot/ankle and it is only suitable for first stage patients. The developed Stewart Platform actuated by PAM produced range of motion of 31.73° which is acceptable range to promote dorsi/plantar flexion. As compared the developed Stewart Platform with S. Krishnan findings of 24.8° for dorsi and plantar flexion which is limited range of motion (ROM). This concluded that the ROM much improved compared to previous researcher.

Table 4.6 below shows the comparison of range of motion between Pneumatic Artificial Muscle and Shape Memory Alloy (SMA).

Table 4.6: Comparison of Range of Motions with Different Actuators

No	Actuators	Range of Motion (ROM)
1	Shape Memory Alloy (SMA) [31]	24.82°
2	Pneumatic Artificial Muscle (12 mm)	31.73°

Table 4.7 present research findings of some authors namely, Takemura et al., Matteo et al. and G.Liu et al regarding dorsa/plantar flexion of their devices. Maximum and minimum movements for dorsa/plantar flexion are around $20°$.

Table 4.7: Maximum and Minimum movement for Dorsa/Plantar Flexion of some authors

Authors	Dorsa Flexion	Plantar Flexion
Takemura et al.	$-20°$	$\sim +20°$
Matteo et al.	$\pm 20°$	$\pm 20°$
G.Liu et al.	$+20°$	$-17.5°$

4.11 Summary

Thus, the summary of this chapter discusses on the results and expected outcome of the prototype. The table of results with respect with the range of motion of the foot/ankle and pulling force of the Pneumatic Artificial Muscle with different diameters was well explained. Three graphs with different loads and how it affects the range of motion was plotted. In addition to this, pressure supplied vs pulling force of different diameters of PAM such as 8mm, 10mm and 12mm was plotted.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this research it is established that the use of Stewart Platform actuated by Pneumatic Artificial Muscle improves the range of motion (ROM) for patient's foot/ankle rehabilitation in biomedical applications. As the PAM is pressurized, the muscle gets expand and shorten in length which pulls the upper platform downwards. Hence, dorsiflexion and plantar flexion movement is achieved. Experiments were run using a designed and fabricated Stewart Platform actuated by PAM and the following conclusions are drawn:

1. Pneumatic Artificial Muscle with the diameter of 12 mm is fabricated in the Stewart platform. The PAM is pressurized up to 5 bars and dorsiflexion, plantar flexion, inversion and eversion movement is achieved.

2. The performance of the current arrays of Stewart Platform actuated by various diameter of PAM was investigated:
    - The Stewart Platform actuated by Ø 8 mm diameter of PAM produced maximum platform angle of 25.31°.
    - The Stewart Platform actuated by Ø 10 mm diameter of PAM produced maximum platform angle of 28.62°.
    - The Stewart Platform actuated by Ø 12 mm diameter of PAM produced maximum platform angle of 31.73°.

3. The developed Stewart Platform actuated by Pneumatic Artificial Muscle produced range of motion of 31.73° which is acceptable range of motion to promote dorsi/plantar flexion. As compared to the developed Stewart Platform with Krishnan (2017) findings of 24.8° for dorsiflexion and plantar flexion which is limited range of motion. This concluded that the range of motion (ROM) much improved compared to previous researcher.

5.2 Recommendations for future work

Instead of using the gyroscope as a sensor, a non-contact type displacement measuring system such as a camera together with an image processing system can be used to measure the displacement of the moving platform on all three directions.

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