DEVELOPMENT OF LOWER LIMB STROKE REHABILITATION MACHINE

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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STATEMENT 1

This thesis is the result of my own investigations, except where otherwise stated.

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Abstrak

Fungsi anggota badan berisiko untuk diserang oleh strok, kemalangan atau penuaan. Lumpuh pada sebelah badan yang mengurangkan kekuatan dan kawalan anggota badan merupakan antara kesan strok. Anggota badan ini boleh dipulihkan melalui senaman. Senaman pasif merujuk kepada otot yang digerakkan dengan bantuan luar manakala senaman aktif merujuk kepada otot perlu menjana daya bagi melaksanakan sesuatu pergerakan. Pelbagai senaman pasif ditujukan khas untuk mangsa strok yang mengalami kesan sampingan yang ringan atau rempuh yang teruk. Senaman ini membantu mencegah kekejangan otot dan kekebasan yang mengehadkan pergerakan otot. Senaman aktif melibatkan tenaga fizikal yang perlu dijana oleh otot.

Tujuan projek ini adalah untuk menghasilkan satu sistem pemulihan yang menggabungkan senaman pergerakan berterusan pasif dan pergerakan berterusan aktif yang meliputi “flexion/extension” kaki. Sistem ini menyediakan maklum balas visual berorientasikan sasaran secara “real-time”. Nilai minimun metrik penglibatan subjek yang sihat menggunakan mesin ini dengan maklum balas visual adalah 24.53% lebih tinggi daripada tanpa maklum balas visual. Ini membuktikan bahawa penggunaan maklum balas visual dapat membantu pesakit untuk fokus sepenuhnya semasa sesi pemulihan lalu menguatkan laluan neuromotor. Senaman pasif menetapkan tiga ulangan bagi setiap 120 saat membantu pesakit menjalankan senaman yang berintensiti tinggi dan berulangan. Komputer digunakan untuk mengisi data dan memaparkan data bagi tujuan pemantauan pemulihan pesakit. Simulasi bagi kaki yang terjejas bagi seseorang yang beratnya 55 kg telah menjalankan simulasi senaman pasif dan mendapat daya purata 35 N. Pergerakan paha mencapai sudut 49.8% daripada purata sudut 120 ° dan lutut mencapai sudut 84.8% daripada purata sudut 143.7°. Daya kaki yang sihat diukur dengan meminta seseorang itu mengenakan daya yang maksimum untuk menolak sistem tersebut. Daya purata 65 N telah diperolehi untuk kes simulasi ukuran daya kaki sihat.

Senaman aktif sesuai untuk pesakit yang telah pulih secara beransur-ansuran. Ia bertujuan untuk memulihkan daya otot melalui pembentukan laluan neural di dalam otak. Daya yang dikenakan oleh kaki pesakit ketika gerakan lanjutan kaki akan diukur oleh alat pengukur daya di tapak kaki. Bacaan dari alat pengukur akan disalurkan ke

myRIO bagi menentukan amoun yang mencukupi untuk membolehkan sistem melanjutkan silinder. Nilai daya pra-set 10 N telah ditetapkan dalam senaman aktif. Program yang dihentikan jika daya yang dikenakan tidak mencapai daya pra-set. Daya yang direkodkan oleh myRIO akan diprosess bagi menilai kadar pemulihan pesakit. Hal ini merupakan satu cara untuk memantau pemulihan motor pesakit secara kuantitatif bagi memberikan motivasi kepada pesakit melalui maklu balas positif sistem tentang kadar pemulihan otot mereka. Sistem yang dibangunkan menonjolkan kelebihan menyediakan maklum balas visual berorientasikan sasaran, sistem dalam pengumpulan data, membantu pergerakan, menyediakan tahap rintangan yang sesuai serta merekodkan tahap pemulihan pesakit.

Abstract

The function of the lower limb can be affected by stroke, accident or even aging. Paralysis on one side of the body is a common effect of stroke which diminishes the strength and control of the lower limb. The lower limb can be rehabilitated by means of exercise. The passive exercise is when the muscle is moved by the means of external force and the active exercise is when the muscle exerted the force necessary to create the motion. Passive range of motion exercises are for stroke survivors who are left with mild to severe paralysation, or paresis. These exercises can help prevent muscle stiffness and spasticity which is the limited coordination and muscle movement. Resistive exercises involve conscious control of the muscle and physical effort exerted into muscular activity to improve neural path formation.

The aim of this project is to develop a combination of rehabilitation system based on Continuous Passive Motion (CPM) and Active Resistive Motion (ARM) which cover the flexion-extension of the hip and knee. The system is providing goal-oriented visual feedback in real-time. The mean value of engagement metric of healthy subjects using this machine with visual feedback was 24.53% higher than without visual feedback. This proved that the use of visual feedback can help the patients to be fully engaged during the rehab session strengthening the neuromotor pathways. The assistive mode of motion is set at three cycles per 120 seconds which allows a high intensity and repetitive form of knee extension and flexion. A desktop computer is used as the data entry and also for data display for monitoring and recording purposes. A simulated paretic limb for a 55 kg subject has carried out the passive mode of motion and an average force of 35 N is obtained. The range of motion of the lower limbs achieved 49.8% of average hip flexion of 120° and 84.8% of average knee flexion of 143.7°. Then healthy leg force measurement is carried out at which the person has exerted the maximum pushing force when the cylinder is at rest in retraction mode and obtained a simulated maximum force of 65 N.

Resistive rehabilitation exercise is for patient who has slowly regain some strength. It aims to regain lost movement after stroke by strengthening the neural pathways in the brain that enable the performance of the movement. The patient is required to exert force on the leg and the force being exerted by the patient during the hip-knee joint extension will be measured by the load cell at the foot rest. The reading from the load

cell is taken as an input to a control system within myRIO to determine whether enough force has been applied to allow the motion. A pre-set force value of 10 N is set in ARM. The system will only complete the hip-knee flexion-extension motion if the paretic limb has achieved the threshold force value and it will end the process when it is unable to achieve the threshold value. This provides a mean for quantitatively monitoring the motor recovery during rehabilitation. This active mode of motion provides positive feedback on the recovery of the muscle strength that motivates the patient to work harder to overcome the threshold force value. The developed system highlight the advantages of goal-oriented feedback on the level of engagement during rehabilitation, the system in driving the actuators, providing suitable resistance level for active exercise based on closed loop control system and to record the achievement of the patient.

CHAPTER 1 INTRODUCTION

1.1 Brief Overview

Stroke is one of the top five leading causes of death and one of the top 10 causes for hospitalization in Malaysia. Stroke is also in the top five diseases with the greatest burden of disease, based on disability-adjusted life years. However, prospective studies on stroke in Malaysia are limited. To date, neither the prevalence of stroke nor its incidence nationally has been recorded.

According to the World Heart Federation, 15 million people worldwide suffer from stroke and nearly five million are left permanently disabled with paralysis and weaknesses every year [1]. This has made stroke as one of the leading causes of disability. Ischemic stroke is the leading cause of death worldwide, accounting for approximately 7.4 million deaths in 2012 [1]; therefore, under the current situation of social aging, the number of stroke patients is increasing. Approximately 50,000 Canadians and 780,000 Americans suffer a stroke each year, resulting in disabilities, reduced mobility, independence, and quality of life [2, 3].

Stroke rehabilitation is defined as a combined and coordinated use of medical, social, educational, and vocational measures to retrain a person who has suffered a stroke to his/her maximal physical, psychological, social, and vocational potential, consistent with physiologic and environmental limitations [4]. An effective rehabilitation program should be able to encourage the improvement of neuroplasticity where the undamaged axons grow new nerve endings to reconnect neurons whose links were injured or severed [5].

Lost function can be recovered with the formation of new neural pathways that can be achieved when the patient is paying full attention in the rehabilitation session and make conscious control over the affected leg. Huge investment of energy is required in the formation of new neural pathways and thus the patient is required to undergo a high intensity exercise on a specific type of motion. Based on principles of motor learning and recovery, the current stroke rehabilitation practices focus on intensive, cognitively demanding, time-consuming and repetitive exercise regiments [6].

Early intervention is identified as critical for stroke patients and shown to improve functional outcomes [7, 8]. Rehabilitation devices aims at developing novel technologies and associated protocols to assist therapists in serving an ever-increasing elderly population and stroke victims [9]. This paper presents the development of a lower limb stroke rehabilitation machine (LLSRM) to help patients improve their lower limb motor function during the rehabilitation program.

1.2 Problem Statement

Post-stroke rehabilitation programs are usually time consuming and labour intensive for both the physiotherapist and the patient in one-to-one manual interaction. The exercises are not conducted in a high intensity and repetitive manner with no methods to quantify the recovery process of muscles. For many patients, sole repetition can be demotivating and frustrating. There is the issue of accessibility and the cost of service in the rehabilitation of the lower limb. The existing rehabilitation equipment's are not affordable for community whose financial status is moderate and lower. Private session with the physiotherapy can be costly. In Kuala Lumpur the price is RM80-RM120 per session [10]. It is clear that the cost of physiotherapy is significant may well be beyond reach of the general population. There are physiotherapy services in the public hospital. A survey of two teaching hospitals in Kuala Lumpur in 2016 showed that 37% of the patients reported that their expectations were not met indicating a relatively average level of services where more than 1 in 3 patients are dissatisfied with the services [11].

1.3 Objectives

To design a machine that is based on goal-oriented visual feedback equipped with Continuous Passive Motion (CPM) and Active Resistive Motion (ARM) of rehabilitation program that can measure the muscle recovery of the paretic limb.

1.4 Scope of the Project

The smart leg rehabilitation system focuses on the development of a combination of both assistive mode and resistive mode of rehabilitation program together with recovery measurement of the patient followed by incorporation of goal-oriented visual feedback. Besides, the algorithm of LabVIEW is used to sequence the rehabilitation programs of the lower limb and involves in the control of the motor during rehabilitation program. Next, this design has the recovery measurement system that can generate quantitative data on the recovery rate of the patients. All the data obtained will be stored in the system.

CHAPTER 2 LITERATURE REVIEW

2.1 Conventional and Robot-Assisted Rehabilitation

One way to overcome the issue of accessibility and the cost of service in the rehabilitation of the lower limb is by using a rehabilitation machine which can reproduce most of the motion made by the physiotherapist. In this case, the machine can help the physiotherapists to overcome the excessive demand to their services by relegating the repetitive tasks to the machine-assisted rehabilitation [12-15]. This can increase the productivity and eventually drive down the costs of healthcare services.

Positive effects on the motor recovery have been reported in many studies on robot-assisted post stroke training when compared to the conventional treatments [16]. Based on the principle of neural plasticity, in order to make the cerebral cortex learn and store the correct movement patterns, repetitive and specific training tasks are to be performed. This is the theoretical basis of rehabilitation treatment. Although the mechanisms of stroke recovery depend on multiple factors, a number of techniques that concentrate on enhanced exercise of the paralyzed limb have demonstrated effectiveness in reducing the motor impairment. High-intensity repetitive task-specific therapy approach is an effective way to improve lower limb motor function after stroke [17, 18]. The most commonly reported treatment approaches provided by rehabilitation robots are (1) continuous passive movement (CPM), (2) active-assisted movement, and (3) active-resisted movement by applying resistance against movement direction [19-22].

However, robot-assisted training with continuous passive movement (CPM) can only provide program that in general is fixed, although there are some machines providing adjustable rehabilitation program. These robotic devices are mainly different from the treatment by a physiotherapist as they have a feeling of the status of the muscle recovery of the patient which can be communicated back to the patients as a form of feedback. These robotic devices are in general unable to adjust the rehabilitation program accordingly to the rate of recovery of the post stroke patients. Besides, this type of motion only effective in temporarily reducing the post-stroke hypertonia [16]. There are still many challenges on integrating robotics into a stroke rehabilitation intervention and questions regarding their efficacy and patient outcomes in the absence of clinically relevant data [18, 23].

2.2 Rehabilitation Therapy

The goal of robotic therapy control algorithms is to control robotic devices designed for rehabilitation exercise, so that the selected exercises to be performed by the participant provoke motor plasticity, and therefore improve motor recovery. Currently, however, there is no solid scientific understanding of how this goal can best be achieved. Robotic therapy control algorithms have therefore been designed on an ad hoc basis, usually drawing on some concepts from the rehabilitation, neuroscience, and motor learning literature. In this review we briefly state these concepts, but do not review their neurophysiological evidence in any detail, focusing instead on how the control strategies seek to embody the general concepts.

One way to group current control algorithms is according to the strategy that they take to provoke plasticity: assisting, challenge-based, simulating normal tasks, and non-contact coaching. Other strategies will likely be conceived in the future, but presently most algorithms seem to fall in these four categories.

2.2.1 Assistive Mode of Exercise

Assistive mode of exercise is the primary control paradigm that has been explored so far in robotic therapy development. Assistive exercise uses external, physical assistance to aid patients in accomplishing intended movements. Assistive exercise interleaves effort by the patient with stretching of the muscles and connective tissue. Effort is thought to be essential for provoking motor plasticity [24, 25], and stretching can help prevent stiffening of soft tissue and reduce spasticity, at least temporarily [26, 27]. Another motivation is that by moving the limb in a manner that self-generated effort cannot achieve, assistive exercise provides novel somatosensory stimulation that helps induce brain plasticity [28]. Another rationale is that physically demonstrating the desired pattern of a movement may help a patients learn to achieve the pattern [29, 30].

Finally, active assistance may have a psychological benefit. To quote a person post-stroke in one of the studies "If I can't do it once, why do it a hundred times?" [31]. This quote emphasizes the fact that active assistance allows participants to achieve desired movements, and thus may serve to motivate repetitive, intensive practice by reconnecting "intention" to "action ".

On the other hand, there is also a history of motor control research that suggests that physically guiding a movement may actually decrease motor learning for some tasks (termed the "guidance hypothesis" [32]). The reason is that physically assisting a movement changes the dynamics of the task so that the task learned is not the target task. Guiding the movement also reduces the burden on the learner's motor system to discover the principles necessary to perform the task successfully.

Guiding movement also appears in some cases to cause people to decrease physical effort during motor training. For example, persons with motor incomplete spinal cord injury who walked in a gait training robot that was controlled with a relatively stiff impedance-based assistive controller consumed 60% less energy than in traditional manually-assisted therapy [33]. Likewise, persons post-stroke who were assisted by an adaptively-controlled, compliant robot that had the potential to "take over" a reaching task for them decreased their own force output, letting the robot do more of the work of lifting their arm [34]. These findings suggest what might be termed the "Slacking Hypothesis": a robotic device could potentially decrease recovery if it encourages slacking; i.e. a decrease in motor output, effort, energy consumption, and/or attention during training.

Because providing too much assistance may have negative consequences for learning, a commonly stated goal in assistive exercise is to provide "assistance-as-needed", which means to assist the participant only as much as is needed to accomplish the task (sometimes termed "faded guidance" in motor learning research). Example strategies to encourage participant effort and self-initiated movements include allowing some error variability around the desired movement using a dead band (an area around the trajectory in which no assistance is provided) triggering assistance only when the participant achieves a force or velocity threshold, making the robot compliant [23].

A study was conducted to study the normal range of motion of the hip, knee and ankle joints on total population of 537 subjects. The hip and knee flexion was found to have a mean value of 120° and 143.7° respectively [35]. These findings are important to design a machine that can achieve such range of motions or at least close to those values.

2.2.2 Resistive Mode of Exercise

Resistive exercise refers to the therapeutic strategy of providing resistance to the patients hemi paretic limb movements during exercise, an approach that has a long history in clinical rehabilitation and clinical rehabilitation devices. The resistive rehabilitation will serve its function after the patient has regained some strength in the muscle. In order to help building the new neural pathways between the limb and the brain is by consciously focus on the motion and being aware of the motion being performed by the patient during the exercise. This requires the patient to generate muscle force to move the limb to overcome the opposing resistive force. The brain is able to rebuild the damage neuron paths through the conscious control of the limb's motion [36, 37]. As such the new rehabilitation machine must have a form of patient interaction to initiate the motion in the exercise and this is part of the characteristic of the rehabilitation machine developed here.

Resistive mode of exercise that is challenge-based helps in the recovery of the impairment in the sensorimotor system. According to the sensorimotor integration theory, the voluntary motor efferent and the afferent sensor experiences together are important and helpful in promoting the recognition of the brain during active-mode motion [38]. Biofeedback can help to improve the outcome in the rehabilitation due to the reason that the patient is able to gain conscious control over the undamaged neuron pathways which are in turn able to promote the restoration of the missing functions.

2.3 Quantifying muscle strength as an indication of recovery

Depressive disorders often follow a stroke. 30% of the post stroke patients will suffer from depression [39]. Current methods of indicating stroke recovery is by Fugl Meyer Assessment (FMA) score [40]. It is a stroke-stroke specific, performance-based impairment index. It is designed to assess motor functioning, coordination, balance, sensation and joint functioning in patients with post-stroke hemiplegia. Scoring is based on direct observation of performance. Scale items are scored on the basis of ability to complete the item using a 3point ordinal scale where 0=cannot perform, 1=performs partially and 2=performs fully. The total possible scale score is 226. It becomes very important to encourage the patients during the whole rehabilitation period. One way to effectively motivate the patient is by making their progress known as a form of feedback [9]. The quantitative representation of the recovery rate of the patients can help to elevate the mood of the patients. The use of portable dynamometry is a common way to measure the strength of muscle in the knee joint, hip and ankle joint. Supine position is most commonly used during the assessment of the strength of lower limb muscle. The differences in strength between the paretic side and non-paretic sides for a specific muscular group is obtained. The smaller the differences indicates a better strength of the symmetry between the limbs of the stroke patient [41]. However, the data collection protocols which include the number of trials, contraction time and resting time intervals are not standardize.

2.4 Visual Feedback in Stroke Rehabilitation

Current stroke rehabilitation guidelines recommend the intensive and repetitive practice of functional tasks after stroke [2]. However, for many patients, sheer repetition can be particularly demotivating. One way of encouraging motivation is by providing patients with visual feedback of their movement in real-time or as offline feedback. Visual feedback gives patients visual of their movements and is known to promote movement re-education [42]. It can be particularly useful for proximal limb segments, which can be hard to see by the individual without contorting the body [43]. Real-time visual feedback plays an important role maintaining and enhancing engagement of patients during stroke rehabilitation exercises.

With visual feedback, the subject focuses on the improvement of his or her performance in an interactive virtual composition. This helps the subject develop integrated, generalizable sensory and motor strategies. The system intuitively communicates to the subject measures of performance and direction for improvement regarding key aspects of his or her movement, while maintaining subject engagement in repetitive task-oriented therapy. Undergoing active rehabilitation promotes neural plasticity for recovery of motor and cognitive function [44]. A research using visual feedback has been conducted for upper extremities. As shown in Figure 2.1D below where three Inertial Measurement Units (IMUs) were placed in each segment of the upper extremity, allowing the determination of the special orientation of the limb. The IMUs were secured to the patient through elastic straps. Real-time visual feedback is shown in mobile app in Figure 2.1C, as a bar displaying the progress in each one of the movements, in relation to the specified goal, repetition count, remaining exercise time and posture [45].

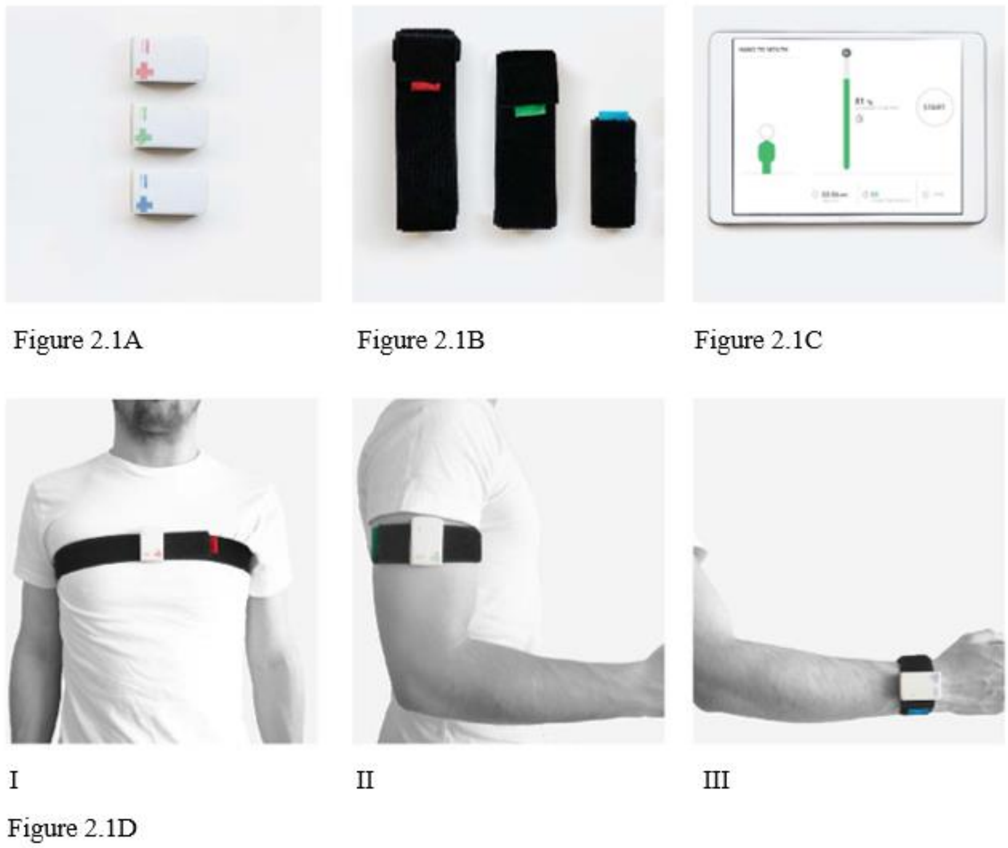

Figure 2.1: System components. (A) IMUs placed in each segment allow determination of the special orientation of the limb. (B) The IMUs are secured to the patient through elastic Velcro® straps. (C)The mobile app provides information on the exercise and real-time visual and auditory feedback. (D)Tracker placement: I) red tracker; II) Green tracker; III) Blue tracker.

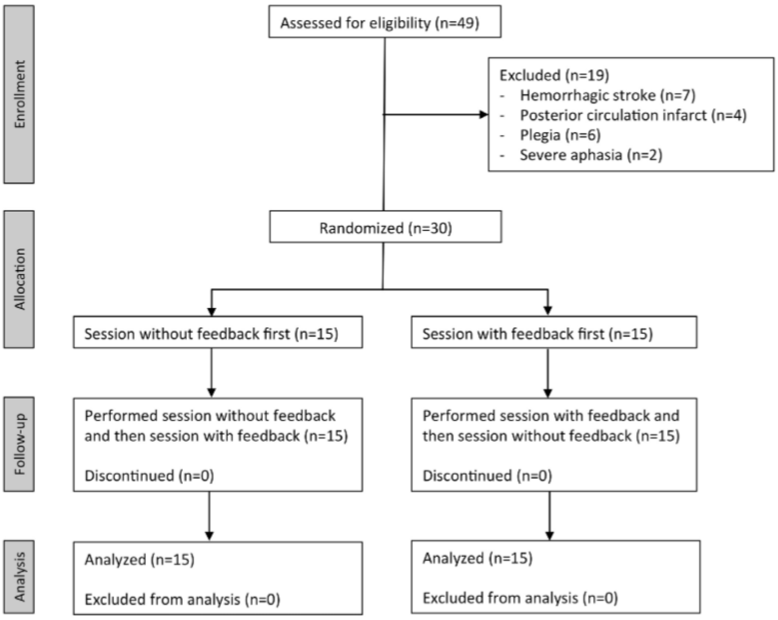

Figure 2.2: Clinical Study Flow Chart [10]

As shown in Figure 2.2 above, 30 participants were allocated to two groups; with and without feedback. Primary outcome was the number of correct movements, defined as those starting at the baseline and reaching the target joint angle, without violating movement or posture constraints. The number of correct movements was higher in the sessions with feedback by an average of 13.2 movements/session and movement error probability was decreased from 1.3:1 to 7.7:1. In short, this study corroborates published data on the benefits of visual feedback [45].

CHAPTER 3 RESEARCH METHODOLOGY

3.1 System and Control Overview

The project begins with the design of mechanical linkages of the LLSRM with SolidWorks. Visual prototyping of the machine is important since it can act as a visual prop to be replicated, improved and learned from. The algorithm would be designed to perform the open loop control on the continuous motion and closed loop active control on the challenge-based motion of the rehabilitation program by controlling the motor. After the mechanical linkage and the control blocks are done, performance evaluation is done by integrating the algorithm to the mechanical linkages to ensure the effective functionality of the LLSRM. Next, recovery measurement system would generate quantitative data on the recovery rate of the patients to ensure the optimal efficacy of the LLSRM for subacute stroke patients. All the data obtained will be stored in the system.

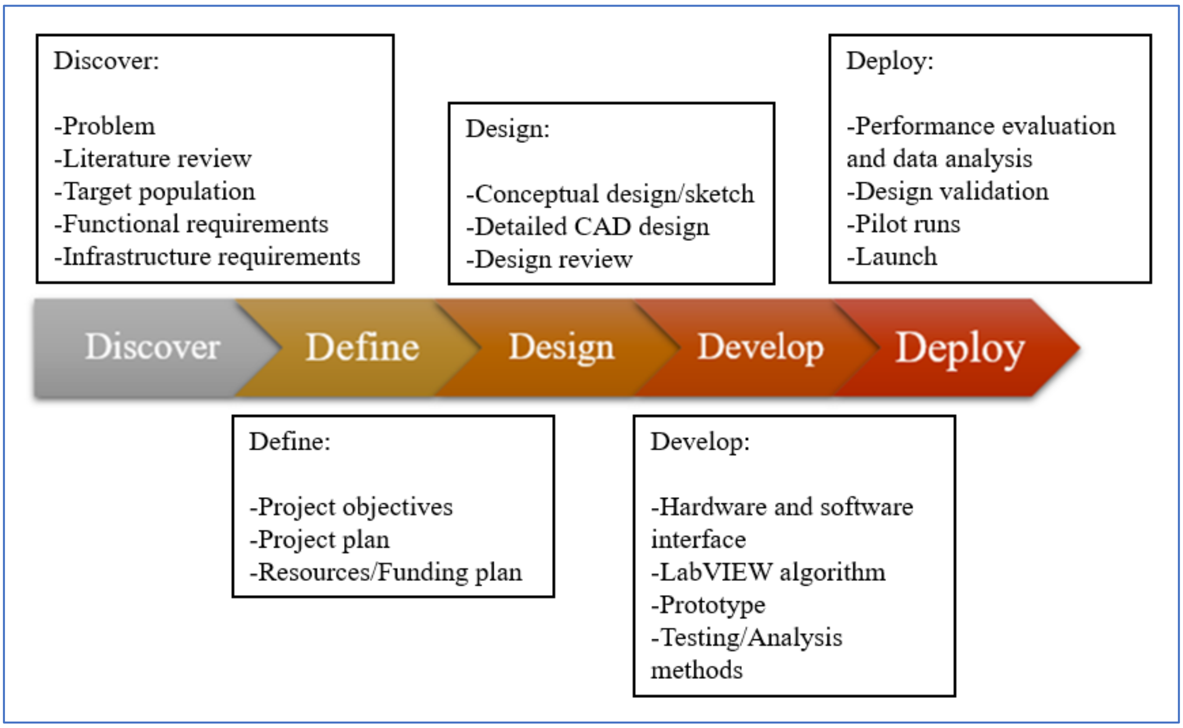

Figure 3.1: Overall Flow of Project Execution Timeline

The overall architecture is shown in the Figure 2 below, a PC running Microsoft Windows 10 will be used to control National Instruments myRIO controller, which will display patient's data in the Graphical User Interface (GUI). The main actuating system of belt drive is chosen. Meanwhile, NI myRIO receives sensor data from

LLSRM and control the motion of the machine via LabVIEW. In addition, a GUI displays the effectiveness of rehabilitation and allow the patient's such as the patient's ID and performance of patient's rehabilitation session data to be stored.

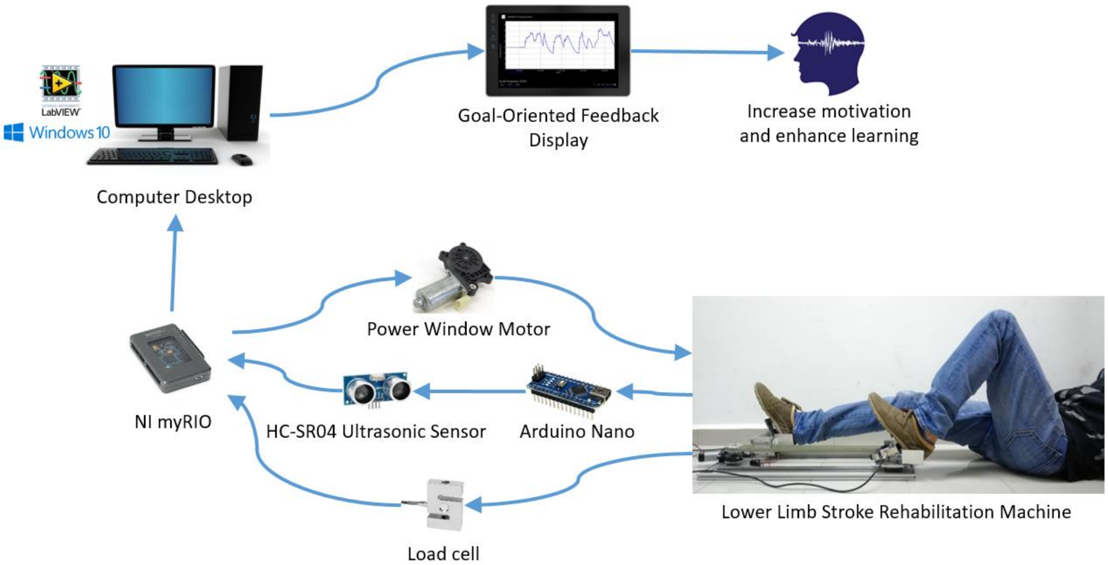

Figure 3.2: Overall system layout of Lower Limb Stroke Rehabilitation Machine

Table 3.1: List of components and their respective roles in the system

Components	Roles & Functions
myRIO	Control automation sequences and to serve as the platform for data acquisition of force sensor and ultrasonic sensor in real time.
Power Window Motor	Actuator to move the foot plates that are connected to the belt drive. The foot plates are actuated in a back and forth motion moving in opposing direction from each other.
HC-SR04 Ultrasonic Sensor	Measures the range of motion of the lower limb by measuring the distance travelled by the foot plate.
Load Cell	To measure the force exerted by the patient's leg
Computer Desktop	To run LabVIEW, store data and display goal-oriented visual feedback.
Apple Ipad Mini	To run LabVIEW Data Dashboard that will serve as the Graphical User Interface (GUI) for the physiotherapists to control the machine wirelessly and display effectiveness of rehabilitation.
Arduino Nano	Interfaces with ultrasonic sensor to export distance data to myRIO via serial communication.

3.2 Measurement of the hip-knee extension-flexion using inertial measurement unit (IMU) sensor

After completion of the prototype, the angular displacement of the hip-knee extension-flexion motion is measured. This measurement is carried out using two IMU sensors. The placement of the sensors on the lower limb are as shown in the Figure 3.3 and Figure 3.4. The two sensors are placed at the thigh and leg respectively. The limb is then placed onto the machine. CPM mode is chosen, extending and retracting the footplate automatically. The angular displacement that is collected from the students will be process by the IMU system.

Figure 3.3: Measurement of angular displacement during hip extension-flexion using IMU sensor

Figure 3.4: Measurement of angular displacement during knee extension-flexion using IMU sensor

3.3 Measurement of range of motion of the limb using an ultrasonic sensor

This measurement is carried out by using an ultrasonic sensor that is placed at the end of the machine. It is placed facing the footplate as shown in Figure 3.4. As it emits a sound wave at a specific frequency, that soundwave can bounce off the surface of the foot plate and be received by the sensor. The unit of the distance obtained is in centimetres.

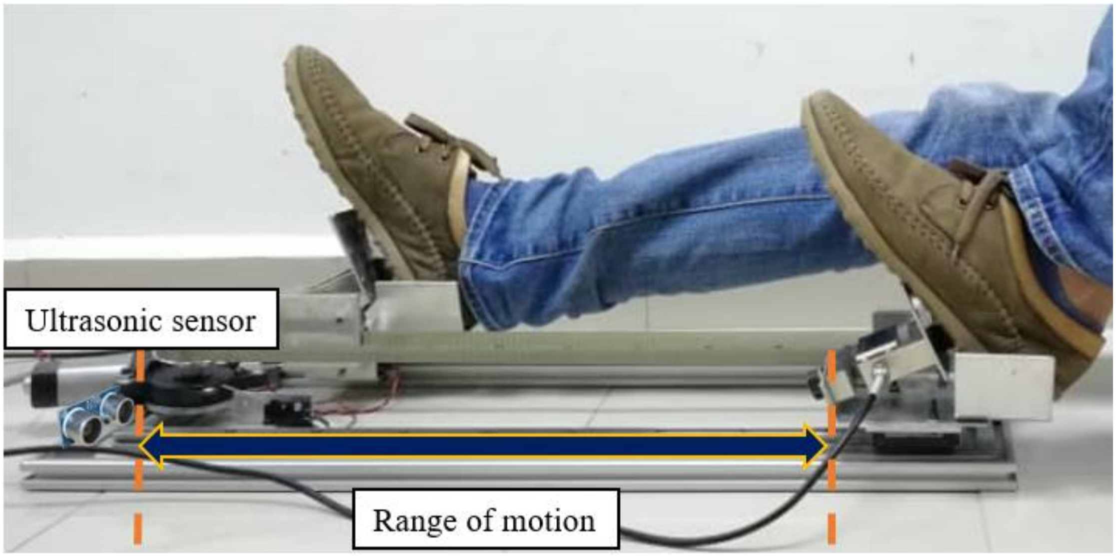

Figure 3.4: Range of motion measurement set up using ultrasonic sensor

3.4 Effect of visual feedback on engagement

In order to investigate whether the application of goal-oriented visual feedback will enhance the engagement of patients in rehabilitation, five healthy subjects were first recruited. They were using the LLSRM in two types of environment, which were with and without visual feedback. At the same time, EMOTIV EPOC+ was worn by them and EMOTIV Control Panel showed the relative changes of a total of six performance metrics, including engagement. Reports were generated with the mean values of all six performance metrics stated inside. Thus, the relationship between goal-oriented visual feedback and engagement can be established by comparing the values of engagement metrics in those two different conditions.

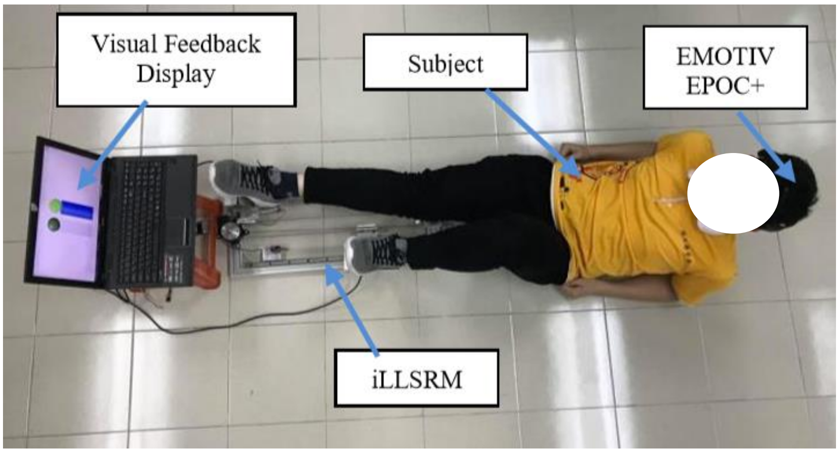

Figure 3.4: System layout for brainwave measurement

3.5 Measurement of the force of the paretic leg in CPM mode

The duration of stroke rehabilitation depends on the severity of the stroke and related complications. A stroke rehabilitation plan will change during the recovery as the patients relearn skills. A rehabilitation session usually lasts for 45 to 60 minutes per day [46]. The number of cycles during CPM can be set according to the physiotherapist's preference. Some patients may experience muscle stiffness which may affect their ability to perform smooth hip-knee extension flexion. Hence, a slower motion would be preferable. The number of cycles per minute can be adjusting accordingly. The non-paretic will be placed on the foot plate and is not required to generate any force as the motion will be performed by the actuation from the motor. The value of force registered along the passive mode of motion has been recorded. This is done to determine the magnitude of force that is contributed purely by the weight of the leg to the load cell.

3.6 Measurement of the force of the non-paretic leg

The force of the non-paretic leg is measured using the same program as CPM with the motor at rest. The position of the foot plate will be at retracted mode as the patient applies force onto the foot plate using their non-paretic leg. All the forces registered at each retraction state of foot plate will be recorded.

3.7 Measurement of the force of the paretic leg in the ARM mode

During the ARM mode, the patient is required to exert force onto the foot plate using their paretic leg when the foot plate is at rest in retraction mode. There exists an interaction between the patient and the machine. The force generated by the paretic limb has to be more than or equal to the pre-set force threshold value consistently during the whole session. The program will stop if the patient is unable to reach the pre-set force threshold value.

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Control system

The completed visual prototype is as shown in Figure 4.1. It is a three dimension (3D) Computer Aided Drawing (CAD) of the machine in SolidWorks. The patient's paretic limb is placed onto the foot plate. The lower limb of the patient is driven by the force transmitted to the belt drive via a power window motor when the machine is activated. The highlights of machine's system consists of 12V DC power window motor as the actuator that drives the belt drive, load cells with measuring range of 50 kg behind the foot plate to measure the force generated by the lower limb, an ultrasonic sensor with measuring range of approximately 500 mm to measure the range of motion of the lower limb by measuring the distance travelled by the foot plate. Timing belt is used as the belt drive because it has teeth that fit into grooves cut on the periphery of the pulleys, hence, reducing the chances of slip and have negligible stretch. The timing belt was tensioned using the fabricated tensioning mechanism as shown in Figure 4.2.

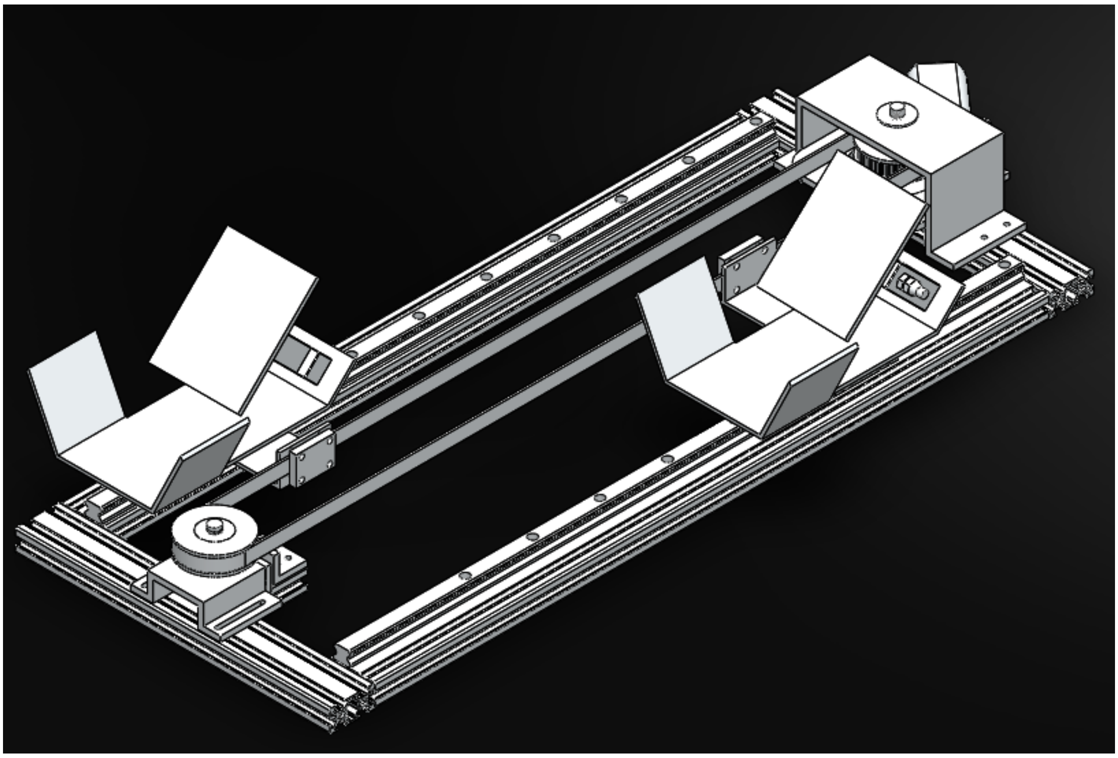

Figure 4.1: 3D CAD SolidWorks drawing of the LLRSM

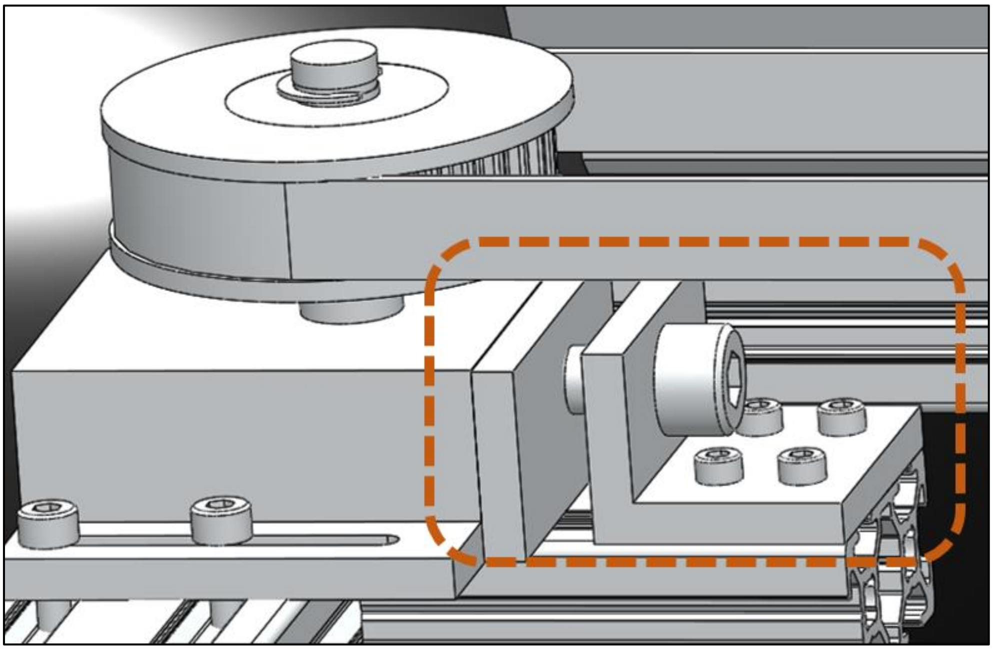

Figure 4.2: Timing belt tensioning mechanism

The foot plates were clamped on to the timing belt as shown in Figure 4.3. They were placed on two carriages respectively that moves smoothly on the 600mm linear guide rails. The foot plates were clamped on to the timing belt in a way that either one of the foot plates will always move in motion towards or away from body. The location at which the foot rests is at an inclined angle of 50° as shown in Figure 4.4 to ensure the comfort of the ankle during hip-knee extension-flexion.

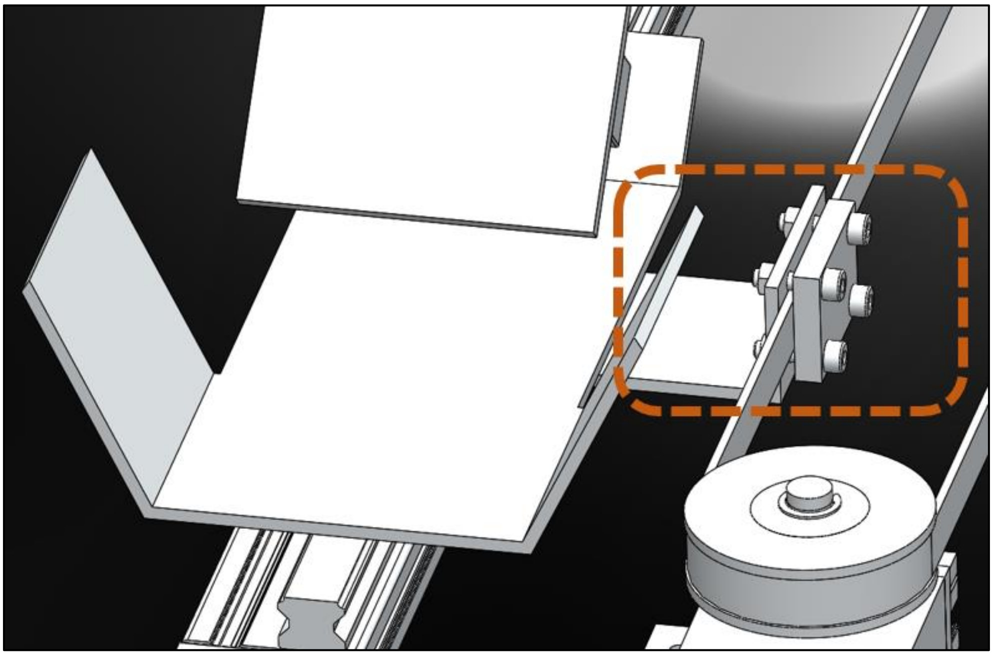

Figure 4.3: Foot plate clamp

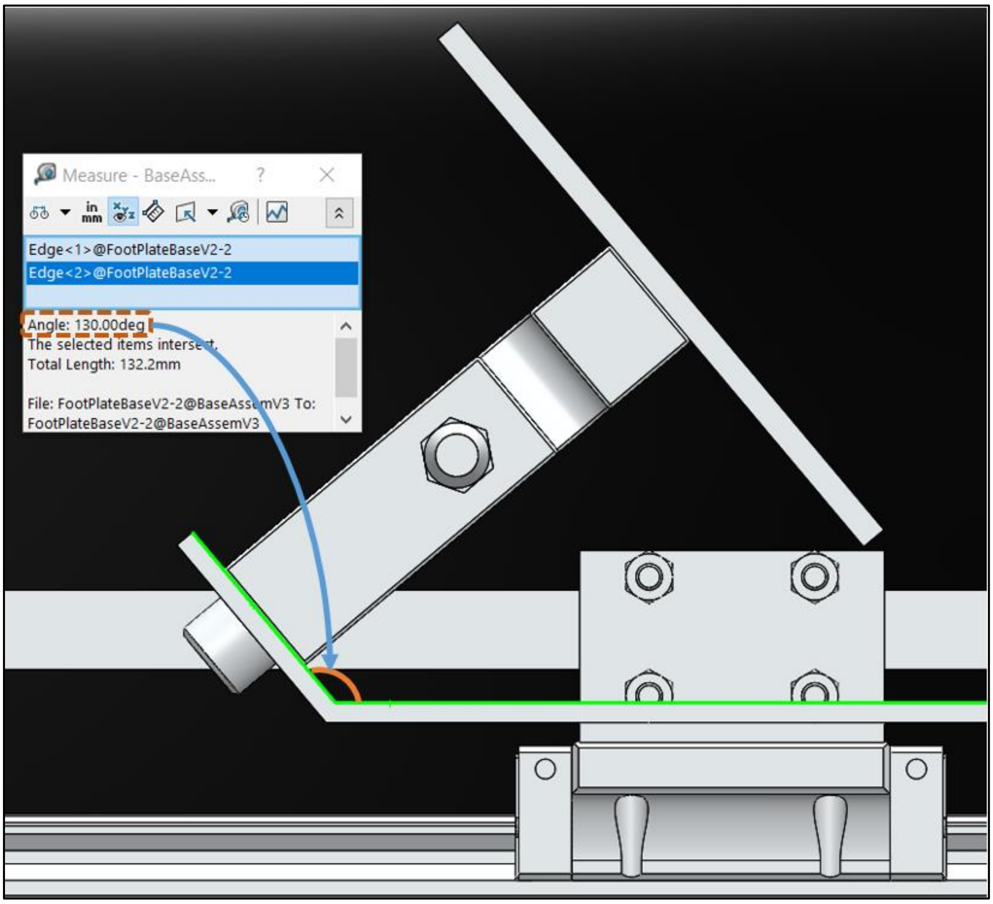

Figure 4.4: Foot plate angle

The angular displacement of the hip-knee extension-flexion has been measured using inertial measurement unit (IMU) sensor. The result obtained for the maximum hip flexion was at 59.8° while maximum knee flexion was at 121.8° as shown in Figure 4.5 and Figure 4.6. Therefore, LLSRM have achieved 49.8% of average hip flexion of 120° and 84.8% of average knee flexion of 143.7°. It is important to understand that this machine does a heel slide motion, hence, it is impossible to achieve hip flexion of above 75% (>90°) of the 120° of average hip flexion.

a) Knee extension a) Knee flexion

Figure 4.5: Angular measurement of knee extension-flexion

Figure 4.6: Angular measurement of hip extension-flexion

4.1.1 Continuous Passive Motion (CPM)

CPM mode is suitable for early phase of rehabilitation as the force to move the limb is driven by the power window motor. A flowchart as shown in Figure 4.7 was made before the algorithm was written in LabVIEW. The coding of CPM mode is as shown in Figure 4.7.

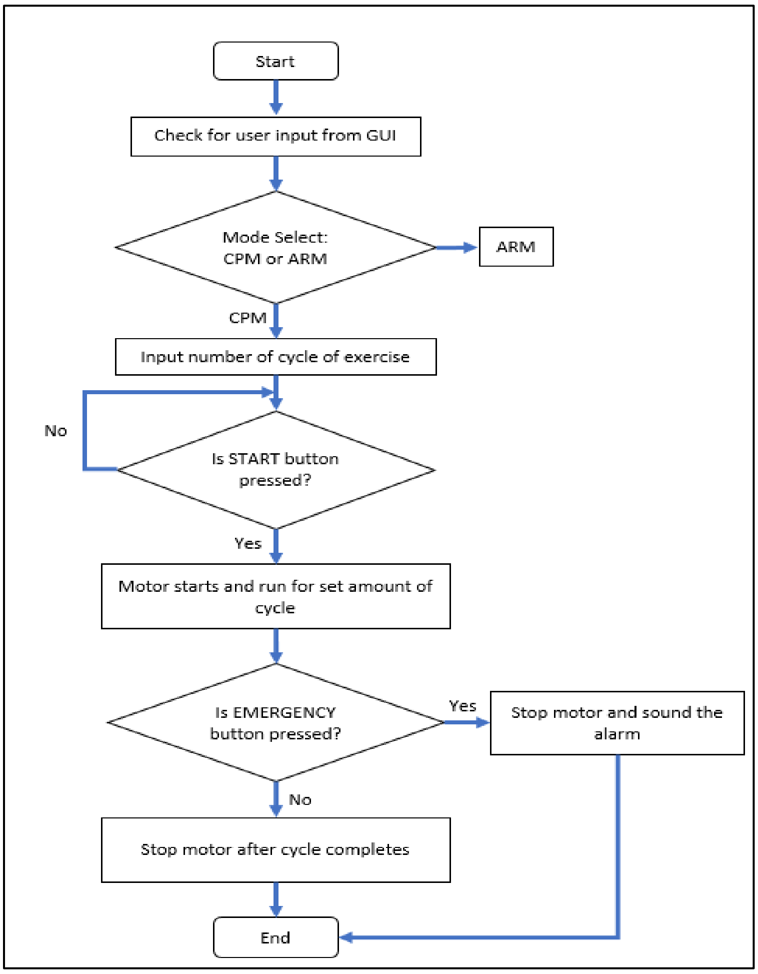

Figure 4.7: Flowchart of the CPM algorithm

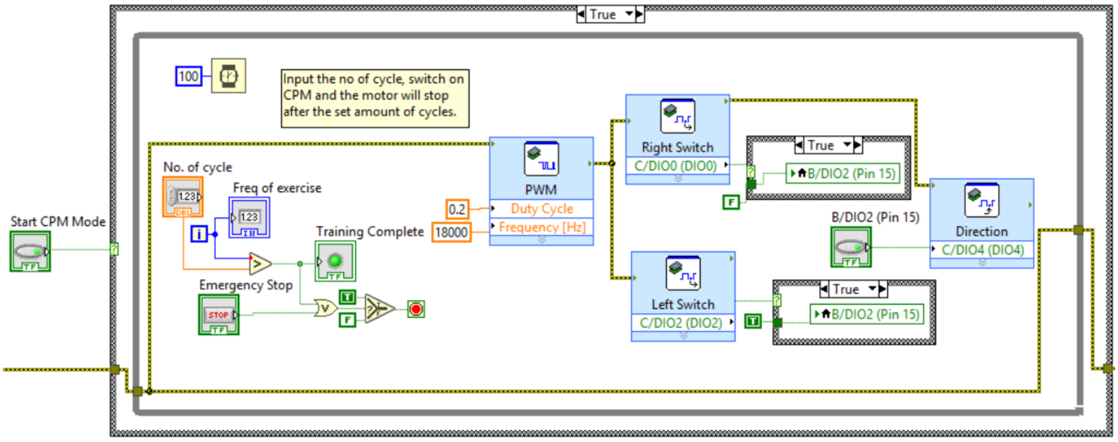

Figure 4.8: Coding of CPM mode

4.1.2 Active Resistive Mode (ARM)

The patient will move on to the ARM once he or she has regained some strength. The force applied by the limb will be measured during ARM. The algorithm flowchart is as shown in Figure 4.9 while the LabVIEW coding is as shown in Figure 4.10. Assuming the right foot is the paretic limb. The load cell input will be taken from the right foot plate. The right foot plate will move away from body to allow for knee extension of motion if the pushing force from the leg achieve the threshold value. Once the limb is fully extended, it will return home in a CPM and ARM is automatically started. This repeats until all the cycles are complete. The threshold force value will increase by 10N each time the patient has successfully achieved the previous threshold value. If the patient fails to achieve that, the patient can choose to go back to CPM.

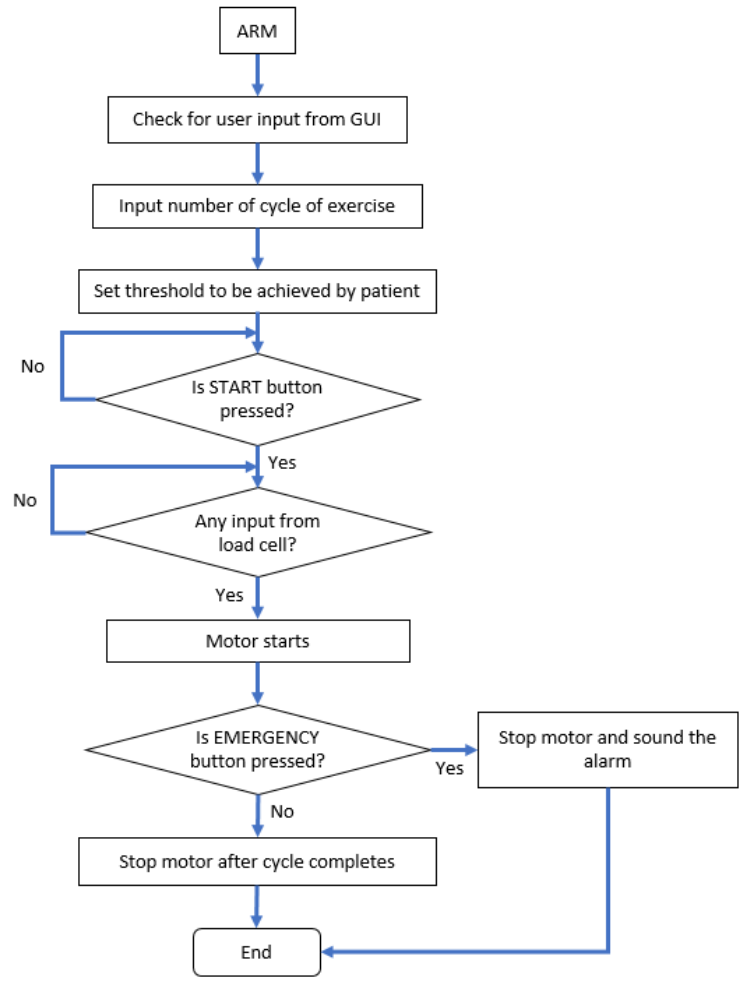

Figure 4.9: Flowchart of the ARM algorithm

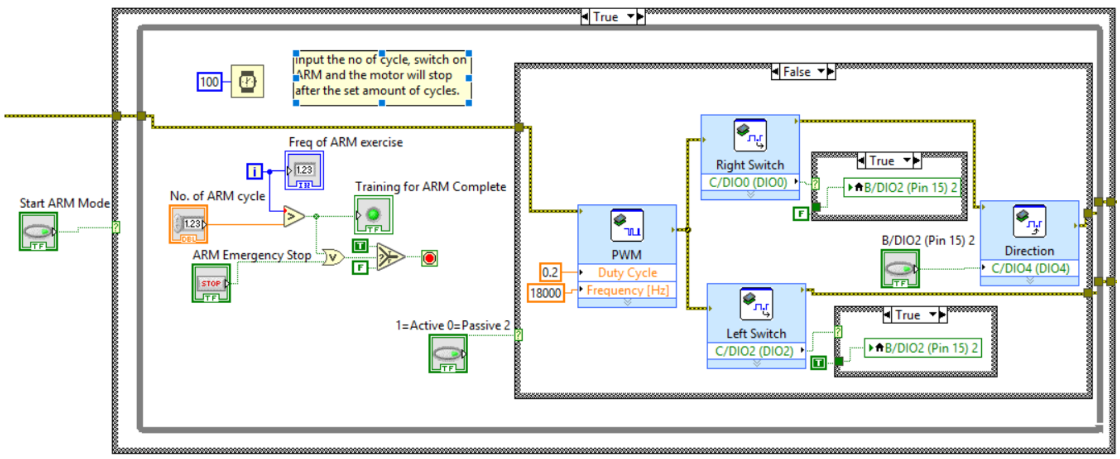

Figure 4.10: Coding of ARM

4.2 System performance

A simulated condition for both CPM and ARM was carried out by a 55 kg-weight person. The average force acting on the system without placing any load on it during passive mode of exercise was obtained. The machine was only running for one and a half cycle. Figure 4.11 shows that there was always an everage error of -0.018 N acting on the system. The system registers only 0.05N when it was at rest. An average of -0.08 N was acting on the load cell at the moment the foot plate started to move from rest as can be seen in the green box region in Figure 4.11.

An average of 0.06 N was also acting on the load cell at the moment the foot plate started to move towards the body as can be seen in the red box region in Figure 4.11. This was only observed during direction switching of the foot plate. This force might due to weight of the metal plate that is placed on top of the load cell. The plate will deflect slightly when the foot plate starts to move suddenly due to inertia thus exerting a small amount of force on the load cell. However, the small amount of force was negligible for this research.

The same trend occured when paretic leg was placed onto the foot plate as shown in Figure 4.12. The machine was running at three cycles which took approximately 92 seconds. However, the average force obtained will include the weight of the leg into the system thus giving a higher value. It is important to note that before the foot was placed on the foot plate, the load cell reading was tared to set any external load (mass of the foot plate) acting on the load cell to zero. As can be observed in the black box region in Figure 4.12, there is some fluctuations in the force measurement. It was due to the subject’s foot trying to adjust its position on the foot plate. Once the machine starts moving a repeating pattern can be observed.

As seen in Figure 4.12, region in the orange box and green box shows drastic decrease in force and increase in force respectively, this is due to the foot plate changing direction. The foot plate changes from a pushing action to a pulling action hence, this puts the load cell in sudden tension whereas in the green box region the load cell is under a sudden compression due to the change in pulling action to a pushing action by the foot plate and the inertia by the leg.

The stready increase in the force after the green box region is due to the motion of the foot toward the body, hip-knee flexion occurs, the amount of resistance the limb is putting on the foot plate depends on the patient's muscles stiffness or flexibility. These factors effect the range of motion of the limb. The stiffer the muscle are, the harder it is to flex the knee and hip due to the limited range of motion.

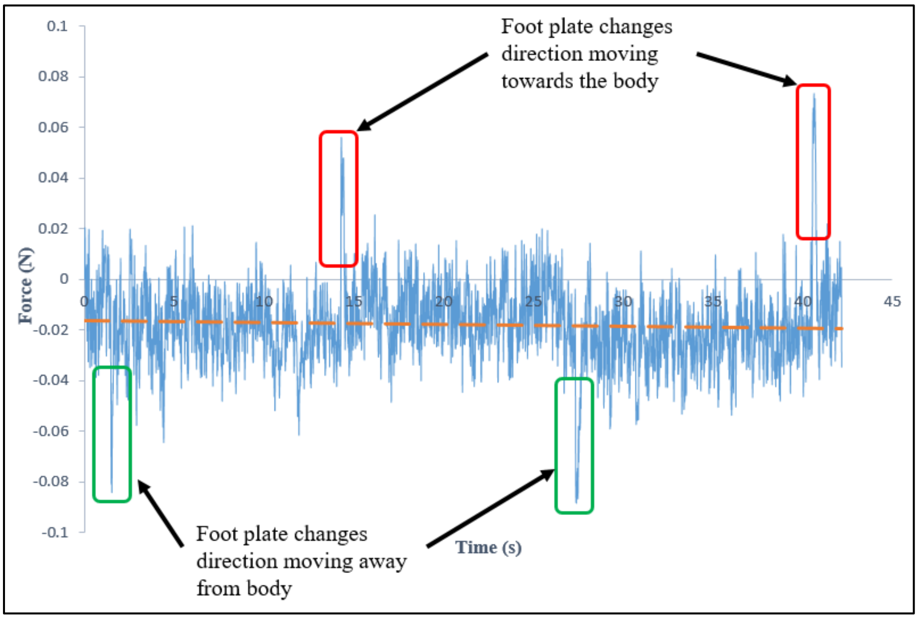

Figure 4.11: Graph of force (N) against time (s) without load in CPM

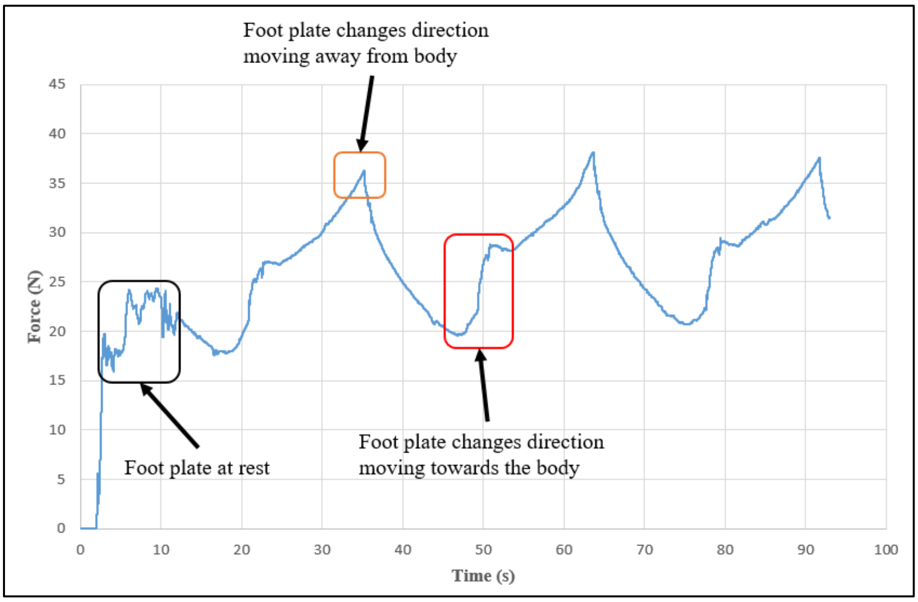

Figure 4.12: Graph of force (N) against time (s) of simulated paretic limb in CPM