EFFECT OF ERROR AUGMENTATION TRAINING STRATEGY ON ENGAGEMENT IN REHABILITATION THERAPY

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UNIVERSITI SAINS MALAYSIA

2019

EFFECT OF ERROR AUGMENTATION TRAINING STRATEGY ON ENGAGEMENT IN REHABILITATION THERAPY

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May 2019

This dissertation is submitted to

Universiti Sains Malaysia

As partial fulfilment of the requirement to graduate with honors degree in

BACHELOR OF ENGINEERING (MECHANICAL ENGINEERING)

School of Mechanical Engineering

Engineering Campus

Universiti Sains Malaysia

DECLARATION

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

Signed………………………………………………… (Alexander Tan Wai Teng)

Date…………………………………………………………………. (29/5/2019)

STATEMENT 1

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

Other sources are acknowledged by giving explicit references.

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ACKNOWLEDGEMENT

First and foremost, I would like to express my utmost gratitude to the School of Mechanical Engineering, Universiti Sains Malaysia for providing the required equipment and the necessary materials to complete my Final Year Project (FYP). The golden opportunity given to me to complete this four-year course in Mechanical Engineering is sincerely appreciated and I believe all the knowledge and technical skills acquired will definitely be valuable for my future career as an engineer. Besides, I would like to express my gratitude to my supervisor, Prof. Dr. Zaidi Mohd Ripin who supervised and supported my research. The guidance and encouragement from my supervisor have always motivated and assisted me in overcoming the challenges encountered. Furthermore, I would also like to acknowledge with much appreciation the crucial role of the staffs of Vibration Lab of School of Mechanical Engineering, Universiti Sains Malaysia (USM), Mr. Wan Mohd. Amri bin Wan Mamat Ali and Mr. Baharom Awang who have provided insight and expertise that greatly assisted the research. Besides that, many thanks go to the coordinator of this course, Dr. Mohamad Ikhwan Zaini Ridzwan, who has invested his full effort in conducting seminar talks to help us achieve our goal. Last but not least, I have to appreciate the guidance and advice given by other supervisors as well as the panels especially in the project presentation.

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LIST OF ABBREVIATIONS

ARM	Active Resistance Motion
BEI	Brain Engagement Index
CPM	Continuous Passive Motion
EA	Error Amplification
EEG	Electroencephalogram
EMG	Electromyography
GUI	Graphic User Interface
LLSRS	Lower Limb Stroke Rehabilitation System
NP	No Perturbations
RD	Random Force Disturbance
USM	Universiti Sains Malaysia

KESAN STRATEGI LATIHAN PEMBESARAN RALAT TERHADAP PENGLIBATAN DALAM TERAPI PEMULIHAN

ABSTRAK

Terdapat banyak strategi dalam bidang pemulihan strok yang boleh meningkatkan penglibatan pesakit di dalam latihan pemulihan diperkenalkan. Satu strategi yang terkini untuk memperbaiki fungsi motor seseorang individu ialah berasaskan ralat. Matlamat kajian ini adalah untuk menyiasat kesan tiga strategi berasaskan ralat, iaitu pembesaran ralat, gangguan daya secara rawak dan latihan tanpa gangguan untuk meningkatkan penglibatan individu di dalam latihan pemulihan dengan menggunakan sistem pemulihan strok anggota bawah (LLSRS). Lima subjek yang sihat (umur: 22.8 ± 0.45) telah menjalani latihan menggunakan mesin pemulihan anggota bawah yang telah direka khas. Tugas latihan yang diperkenalkan terdiri daripada penjejakan bar penunjuk visual pada paparan grafik LabVIEW dengan mengawal daya diberikan oleh kaki paretik. Tindak balas otak dan penglibatan subjek apabila bertindak terhadap latihan pemulihan yang diperkenalkan diukur menggunakan elektroencephalogram (EEG) yang diperolehi daripada isyarat otak yang diukur berdasarkan alat Emotiv EPOC +. Keputusan menunjukkan bahawa paradigma latihan pembesaran ralat dapat meningkatkan tahap penglibatan ($p < 0.05$) dalam subjek yang sihat semasa latihan pemulihan berbanding dengan terapi pemulihan konvensional. Kajian ini juga mengkaji keberkesanan di antara strategi-strategi latihan yang digunakan untuk menggalakkan penglibatan subjek yang sihat, dan keputusan menunjukkan tidak ada perbezaan yang signifikan ($p > 0.05$) di antara keberkesanan tiga strategi latihan yang dinilai. Kajian klinikal akan dijalankan pada masa depan untuk menilai keberkesanan rawatan pemulihan menggunakan LLSRS yang direka dalam memberikan impak positif yang sama kepada golongan pesakit strok.

EFFECT OF ERROR AUGMENTATION TRAINING STRATEGY ON ENGAGEMENT IN REHABILITATION THERAPY

ABSTRACT

There are numerous strategies in the field of stroke rehabilitation which help to enhance the patients' engagement in the rehabilitation exercises. One of the most updated strategies for improving an individual's motor rehabilitation includes a robotic interface known as error augmentation. The goal of this study was to evaluate three error augmentation training strategies (error amplification (EA), random forces disturbances (RD) and training without perturbations (NP)) based on the engagement level during the rehabilitation exercise of healthy individuals. This will form the framework for future application to sub-acute stroke survivors using the developed lower limb stroke rehabilitation system (LLSRS). Five healthy subjects (5 males; age: 22.8 ± 0.45) performed the experiment using the designed LLSRS. The training task consisted of tracking a targeted visual indicator bar presented on a LabVIEW graphic user interface by controlling the amplitude of force applied by the leg. The brain response and sustained engagement of the subject when responding to the different training strategies are studied using electroencephalogram (EEG) obtained from the measured signals of the brain activities based on the Emotiv EPOC+ headset during the exercise. The results demonstrated that the error-augmentation training paradigms can improve the engagement level ($p<0.05$) in healthy subjects during a rehabilitation exercise compared to conventional rehabilitation therapy. The results also showed that there is no significant difference ($p>0.05$) between the effectiveness of the training strategies in enhancing the engagement of a subject. A clinical trial will be required to further investigate the efficacy of the rehabilitation treatment using LLSRS in providing similar training advantage to sub-acute stroke patients.

CHAPTER 1

INTRODUCTION

1.1 Overview of Stroke Rehabilitation

According to the World Heart Federation, nearly 15 million people worldwide suffer from stroke every year and about five million stroke patients are left permanently disabled with paralysis and weaknesses [1]. Stroke is one of the top five leading causes of death in Malaysia, besides that, it is one of the top ten prominent causes for hospitalization [2]. Hemiparesis (one-sided weakness), and hemiplegia (one-sided paralysis) are the common physical effect of stroke which weakens the strength of the limbs and affect the control of motor systems. Roughly 80% of patients will experience motor weakness after suffering from a stroke [3].

Generally, stroke can be classified into two major types, known as ischemic stroke and hemorrhagic stroke. Ischemic stroke occurs due to the presence of blood clot within a blood vessel and results in obstruction of blood supply to the brain. Consequently, part of the brain will lose its function due to oxygen deprivation [4]. On the other hand, a hemorrhagic stroke occurs due to the bursting of the blood vessel that supplies oxygen and nutrients to the brain and causes blood spillage in the brain [5].

Stroke rehabilitation is an extensive journey towards recovery which aims to recover motor impairment of a stroke patient. The objectives of the rehabilitation exercise are to improve the brain and the body function of the stroke survivors and aids to prevent the recurrence of stroke. An effective rehabilitation program should be able to enhance the improvement of neuroplasticity, where the undamaged axons grow new nerve endings to reconnect neurons whose links were injured or severed [6]. The lost functions of the brain can be slowly recovered with the forming of new neural pathways. Based on principles of motor learning and recovery, current stroke rehabilitation practices focus on intensive, cognitively demanding, time-consuming and repetitive exercise regiments [7].

Robots play significant roles in healthcare as incorporating healthcare robots can reduce medical errors, enhance diagnosis, and also increase the effectiveness and quality of healthcare delivery. Healthcare robots are considered to be one of the most useful applications of robotic technology due to the precision provided and the capability to work without fatigue [8]. Rehabilitation robotics are fairly important in the current society with the use of various robots as therapy aids or as assistive devices. There are several smart rehabilitation robotics on the market which will help in the mobility training for individuals who are suffering from impaired movement due to the effect of stroke [9].

1.2 Overview of Error Augmentation Strategies

In recent studies, researches have explored novel possibilities for incorporating various robotically-enhanced training strategies in the field of rehabilitation. There is a drastic growth in the trend towards integrating feedback technology to enhance the motor learning of stroke and Traumatic Brain Injury (TBI) survivors and was proved to be able to reduce the impairment of motor more effectively compared to the conventional therapy [28].

One of the most recent feedback technology for intensifying motor recovery is through error augmentation strategies [29] which employed incorrect feedback to enhance motor recovery. This technology utilizes robotic devices to identify the subjects' movement errors from a preset trajectory, and artificially amplify the errors either through the force field, distortion and modification of the visual feedback, and amplification of the timing error [30-31]. The presence of the error in visual input will motivate the subjects to strengthen and focus on their motor control as they are required to oppose the error-driven disruption to their movements, and this approach will also motivate the subjects as minor errors will seem large due to the amplification.

Error feedback learning processes are believed to be the key to promote neuroplasticity and able to enhance the reacquisition of motor function due to the fact that numerous forms of learning are actually error driven processes. Recent studies have suggested that the human motor system is capable of detecting kinematic errors in the previous trial and amends the errors in subsequent trials to achieve the assigned task in a gradual manner [32-33].

1.3 Problem Statement

Current stroke rehabilitation practices focus on intensive, cognitively demanding, time-consuming and repetitive exercise regiments. The available rehabilitation programs are time-consuming and labor intensive due to the manual interaction between the physiotherapist and patient. The number of physiotherapists available at clinical departments is limited and this process will be extremely exhausting for the physiotherapist and patients after a number of repetitions. Besides, there is the issue of the cost of the rehabilitation programs available currently. Private physiotherapy session is way beyond the reach of the general population.

In addition, boredom and demotivation are unavoidable during the rehabilitation program due to the boring and high repetition manner of exercise. One of the most updated strategies in improving motivation is by introducing the error feedback of the patient’s movement or timing. This approach can be further developed by incorporating a robotic interface known as error augmentation to the rehabilitation therapy. Engaging within rehabilitation experience can promote neural plasticity for recovery of motor and cognitive function, thus the patient's motivation and engagement level are important factors that must be considered in the development of rehabilitation programs. [27]

1.4 Objectives

There are two main objectives of this study:

i. To design and develop a Lower Limb Stroke Rehabilitation Machine equipped with Continuous Passive Motion (CPM) and Active Resistance Motion (ARM) rehabilitation programs incorporated with error augmentation robotic training strategies to enhance the engagement of a stroke patient during the rehabilitation therapy.

ii. To evaluate three robotic training strategies (error amplification, random forces disturbances, and training without perturbations) on the improvement of engagement throughout the rehabilitation therapy via electroencephalograph (EEG).

1.5 Scope of Project

A smart lower limb rehabilitation machine equipped with Continuous Passive Motion (CPM) and Active Resistive Motion (ARM) rehabilitation program incorporated with various error augmentation based robotic training strategies is developed for the stroke patients to carry out rehabilitation exercise. Algorithms of LabVIEW are developed in order to sequence the control and response of the machine based on various input parameters. The programs which represent which of the proposed robotic training strategies (error amplification, random forces disturbances and training with no perturbations) are also developed using LabVIEW algorithm. Five healthy subjects are selected to undergo the selected exercise with each of the training strategies at a time and the mean value of engagement metric during each rehabilitation exercise is studied by the electroencephalogram (EEG) obtained from the measured signals of the brain activities using Emotiv EPOC+ headset and the Emotiv Control Panel software. The data obtained from the experiment is statistically analyzed to evaluate the significant effect of each robotic training strategy.

CHAPTER 2

LITERATURE REVIEW

2.1 Lower Limbs rehabilitation machines

Robots or machines for stroke rehabilitation for lower limbs have been created and applied in health institutions and shown to assist in the recovery of stroke patients who are still suffering from hemiparesis. These lower limb rehabilitation robots are developed to provide motion of the various joints of lower limbs with various activities and modalities. There are a variety of exercise that involve training of multiple joints, for instance, leg press, gait trajectory following, cycling, and customized movement. Generally, one or several kinds of these exercises can be selected in order to accomplish different aspects of recovery [10-11].

Lower limb rehabilitation machines can be generally categorized into two main categories, which is end effector robots and exoskeleton robots [52]. Based on their principles of rehabilitation, end-effector robots are usually platform-based or footplate-based; while the exoskeleton robots are leg orthoses-based or treadmill-based.

Exoskeleton robots are usually fixed in different parts of the lower extremities, while producing forces or torques to assist the exercise. However, the exoskeleton robots may be ineffective in improving certain stroke survivor’s lower limb motor function due to its poor adaptability. On the other hand, end-effector robots are generally at a certain point in contact with the patient’s lower limb. The end effector robots have higher adaptability to different patients as there is no restriction on the patient’s movement [53].

2.2 Working Angle of for Lower Limbs rehabilitation machines

Leg press exercises are used extensively in sport and neuromuscular rehabilitation. It is utilized to strengthen the muscles of multiple joints of the lower limbs. This leg press exercise can activate leg muscles in a similar way compared to bodyweight exercises such as hip thrust and chair rise. Besides that, through this exercises, most stroke patients have not only improved their strength on both affected and non-affected legs, but also improved in the sense of balance, walking ability, and functional performance [12, 13].

The study by Da Silva et al. showed the effect of mechanical changes and loads towards lower limb muscles activity while performing different leg presses (LP) exercises. In this study, 14 subjects participated to performed three different types of LP exercises, which are LP low (LPL), 45 degrees LP (LP45) and LP high (LPH) and the electromyographic activity of various muscle groups: vastus lateralis (VL), rectus femoris (RF), gastrocnemius (GAS), gluteus maximus (GM), and biceps femoris (BF) was recorded. The experimental results shown that performing LPL can induce greater vastus lateralis and rectus femoris (quadriceps) activation ($p<0.05$); while performing HPL will induce greater gluteus maximus activity ($p<0.05$) [14].

A study by Roass et al. was conducted to study the normal range of motion of the hip, knee and ankle joints based on 210 hips, 180 knees and 192 ankle joints. The arcs of passive motion were measured by techniques suggested by the American Academy of Orthopaedic Surgeons. The results found that the hip and knee flexion has a mean value of 120° and 143.7° respectively [15]. These findings are important in designing the range of motion and the structure for the lower limb rehabilitation machine.

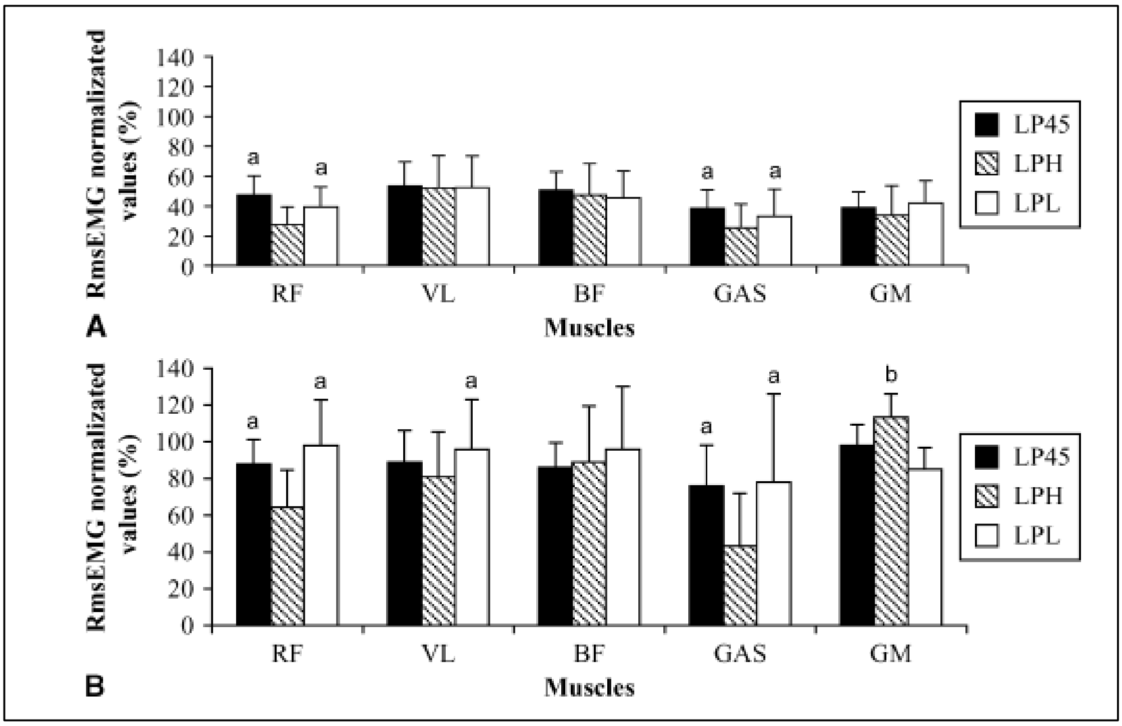

Figure 2-1: Root mean square (Rms) of electromyographic (EMG) values of the muscle activation of RF, VL, BF, GAS and GM while performing different types of LP exercises at a effort level of 40% and at an effort level 80%. [14]

2.3 CPM coupled with active movement

Recent studies are focusing on the use of a robotic system effect to keep the patient at a high engagement level in therapy using approaches such as assist-as-needed strategies and measures of patient movement intent. These approaches are promised to be effective in maximizing the patient’s engagement by enabling the patients to achieve the desired motions with minimum assistance from the robotic system [16].

Besides, there is evidence that shows the effect of passive movements in altering motor recovery is insufficient [17], and the study by Hogan et al. has found that the patients have to be actively engaged and attempted to move during the rehabilitation process so that they will be able to experience the benefit from the robotic rehabilitation system [18].

Lynch et al. conducted a controlled, randomized trial on a group of 32 stroke patients, and the results have shown that continuous passive movement type of therapy can bring potential benefits for the patients' neural recovery, but it does not provide sufficient improvements in altering the motor function recovery [17]. However, by integrating continuous passive movement with active movement, this approach has found to be beneficial to the motor recovery of a stroke patient based on the evidence from several studies [18-19]. Assist-as-needed strategies have been further developed to be integrated with controllers to estimate the patient's effort and engagement in real time based situation, thus the assistance by the robots can be altered effectively.

2.4 Application of Gaming System in Stroke Rehabilitation

Many of the treatments for severe, moderate, or mild stroke have highlighted the need to find alternatives using new technologies to enhance recovery of the stroke patients. By incorporating gaming as a mean of rehabilitation can help to increase repetitions and engagement level during rehabilitation exercise [20]. At present, this technology based on virtual reality has made significant impacts on the treatment of stroke survivors, where the inclusion of various sensors greatly improvises the user-virtual environment interaction. This technique, together with visual feedback can be used to receive data from the brain and muscles, and provide real-time virtual reality feedback for the patient. Engaging within rehabilitation experience can promote neural plasticity for recovery of motor and cognitive function, thus the patient's motivation and engagement level are of important factors that must be considered in the development of rehabilitation programs [27].

Recent research presents the development of an application that includes a set of games based on virtual reality, which proposes the execution of movements of upper and lower extremities in order to aid stroke patients to regain the motor properties. This technology has increased motivation in the development of exercises, where interaction with digitally reconstructed scenarios generates a level of immersion to retain the engagement of the patients and influence them to continue recovery exercises or tasks [21]. In the work of Yavuzer et al., a controlled, randomized, assessor-blinded clinical trial on hemiparetic patients (n=20) is designed to study the effects of "Playstation EyeToy Games" on the recovery of upper extremity motor and upper extremity related motor functioning of the patients suffering from subacute stroke. The results showed that incorporation of gaming systems with conventional stroke rehabilitation program have significantly enhanced the hand and upper extremity-related motor function in subacute stroke patients based on the mean change score of the FIM self care score (CI=95%; p=0.018) [22].

2.5 Measurement of Engagement via Electroencephalography (EEG)

Electroencephalography (EEG) offers an alternative to access and record the neural activity of an individual, where the patterns of brainwave generated by thoughts can be obtained and further analyzed by a computer. EEG is one of the common techniques used for the measurement of task engagement. Engagement level can be referred as the level of immersion of an individual at a particular moment and it is a combination of concentration and attention. According to Berka et al., engagement index indicates the efficiency and involvement of people in information-gathering, visual scanning and sustained attention [23]. Pope et al. and Freeman et al. proposed that the engagement index can be measured and calculated by computing the ratio of the different brain waves of (Beta/(Alpha + Theta)) [24-25].

McMahan et al. carried out an experiment to compare the different engagement indices using the EMOTIV EPOC device [26]. The study suggested that the EMOTIV EGG can be employed to evaluate the engagement level of the game players while they are experiencing a different level of gaming events. The work concluded that (Beta/(Alpha + Theta)) is the preferred algorithm for calculating the engagement levels via this EEG device as it is capable of extenuating noise from individual sensors.

2.6 Characteristics of EEG Signals

Electroencephalogram (EEG) is the summation of the activity of the enormous amount of brain cortex neurons which are continuously interacting with each other [36]. It has been widely utilized in the fields of neurophysiology, e.g. evaluation of the neurons' interactions intricated in consciousness. The simultaneous activity of an individual's cortex neurons will generate distinct types of brain rhythms [35]. There are four main categories of brainwaves, depending on their frequency that is associated with the brain activity [36-37]. The four main categories are:

- Beta rhythm (β): Beta wave is in the frequency range of 13-35 Hz. It is related to alertness, consciousness and motor behavior of a person.
- Alpha rhythm (α): Alpha wave is recorded from the occipital lobes of a person during wakeful relaxation. Alpha wave has a range of frequency between 7-13 Hz.
- Theta rhythm (θ): Theta wave is in the frequency range of 4-7 Hz, and this is obtained during deep relaxation, sleep, or drowsiness.
- Delta rhythm (δ): Delta wave has the lowest frequency range comparatively of 0-4 Hz. It is recorded during low brain activities, e.g. moderate and deep sleep.

2.7 Error Augmentation and Error Reduction Paradigms in Stroke

In recent studies, there is a drastic growth in the trend towards integrating feedback technology to enhance the motor learning of stroke and Traumatic Brain Injury (TBI) survivors and was proved to be able to reduce the impairment of motor more effectively compared to the conventional therapy [28]. Two robotic therapy approaches (error-augmentation and error-reduction) were developed as the means of augmentation or reduction in the timing errors respectively. Both error-augmentation and error-reduction approaches which involve the modification of haptic feedback were suggested to be proficient in enhancing the recovery of upper extremity's motor function among stroke patients [34].

However, results from the study search carried out by Liu et al. suggested that there is an adequate level of evidence that showed error-augmentation is more effective in enhancing the performance and recovery of the motor function among stroke patients compared to conventional rehabilitation practices and error-reduction strategy [54]. Review by Liu et al. has shown that the error-augmentation paradigm exhibited auspicious effects for the rehabilitation which involved post-stroke upper extremity.

2.8 Error Augmentation Strategies in Stroke

Error feedback learning processes are considered to be the key to promote neuroplasticity and able to enhance the reacquisition of motor function due to the fact that numerous forms of learning are actually error driven processes and recent studies have suggested that the human motor system is capable of detecting kinematic errors in the previous trial and amends the errors in subsequent trials effectively. [32-33]

One of the most updated feedback technology for intensifying motor recovery is through error augmentation strategies [29]. Error augmentation strategies employed incorrect feedback to enhance motor recovery. This technology will utilize robotic devices to identify the subjects' movement errors from a preset trajectory, and artificially amplify the errors either through a force field, distortion and modification of the visual feedback, or amplification of the timing error [30-31]. The presence of the error in visual input will motivate the subjects to strengthen and focus on their motor control as they are required to oppose the error-driven disruption to their movements, and this approach will also improve the motivation of the subjects as minor errors will seem great due to the amplification.

Marchal-Crespo et al. have investigated and compared the effect of various robotic-training paradigms that includes errors augmentation (error amplification and random force disturbance) on the motor learning and brain activation of thirty four healthy subjects while carrying out a specific task, which is to track the Lissajous figure displayed on the graphic user interface by coordinating both legs in a movement pattern which represents the gait trajectory. The behavioral data obtained suggested that the degree of error augmented to the task have to be based on the skill level possessed by each subject. However, the effect of the proposed strategies upon brain activation, motor learning, and motivation among the patients will require further research and investigation [34].

CHAPTER 3

METHODOLOGY

3.1 Structure of the Lower Limb Stroke Rehabilitation Machine

A lower limb stroke rehabilitation machine was developed and employed to conduct the experiment. It is a rehabilitation machine which was specifically designed for sub-acute stroke patients to undergo stroke rehabilitation exercise. Figure 3-1 below shows the lower limb stroke rehabilitation machine.The machine is powered by a 12V geared DC motor, which is to actuate the foot pedals in a back and forth motion moving in opposing direction from each other via belt drive mechanism. The rehab machine allows the patient to experience hip and knee flexion and extension motions in the sagittal plane which resemble a stationary stepping motion. The robot was incorporated with load cells (PUSHTON PSD-51) located below the foot pedals to measure the interaction force between the patient and the machine. The machine was integrated with calf supports to stabilized and support the paretic leg. The designed calf supports were able to follow the motion of the patient's calves and compensate the gravity effect by two sets of spring on each support. The stiffness of the spring can be adjusted to provide sufficient lift force depending on the weight of the lower limb of the specific patient.

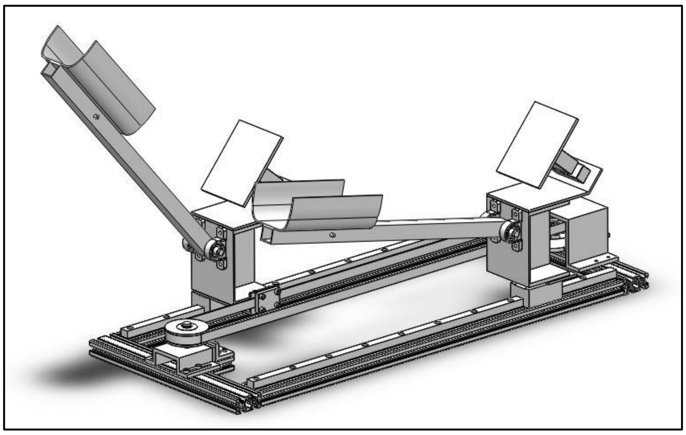

Figure 3-1: The CAD design lower limb stroke rehabilitation machine.

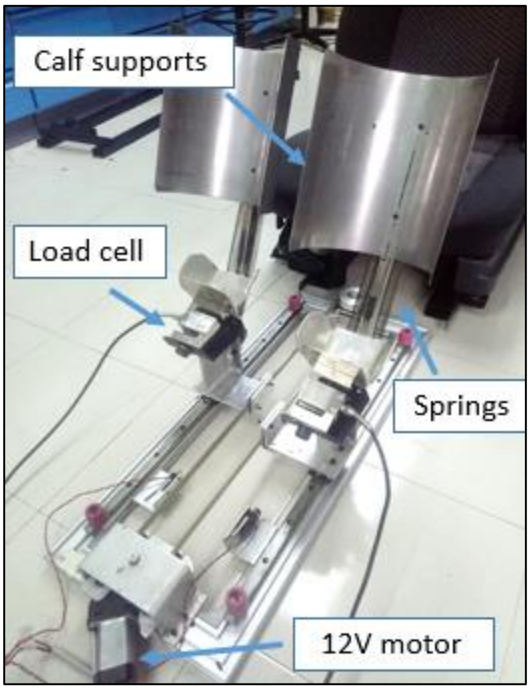

Figure 3-2: The lower limb stroke rehabilitation machine.

3.2 Overall Architecture of the System

The main components of the machine are listed in Table 3-1 and the overall architecture is as shown in Figure 3-3. The control and sequence of the stroke rehabilitation machine are controlled via the NI myRIO - 1990 microcontroller based on the LabVIEW algorithm. The microcontroller also plays the role of acquisition of the data such as the force applied by the muscles from the load cells. A host PC running Microsoft Windows 10 is used for the purpose of controlling and interfacing with the myRIO microcontroller. At the same time, the monitor display of the PC will be used to provide a means of visual feedback to the patient. An Emotiv EPOC+ headset will be worn by the stroke patients concurrently during the rehabilitation exercise to study and measure the engagement level and the brain responses of the patient using the EMOTIV Xavier control panel.

Table 3-1: List of components and their respective roles in the system

Components	Functions
NI myRIO - 1990	Serve as the role of acquisition of the data such as the magnitude of force applied from the load cells and to control and sequence the machine.
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.
Load Cell (PUSHTON PSD-51)	To measure the force exerted by the patient's paretic leg.
Computer	Controlling and interfacing with the myRIO microcontroller via LabVIEW, store data and display the error augmentation training interface.
Measuring Amplifier (HBM – MVD 2510)	Used for signal conditioning so the signal measured by load cell can be amplified and converted into an appropriate output value.
Motor Driver (Cytron – MD10C)	Acts as an interface between the control circuits and the 12V motor by taking a low current control signal and then amplify it into a higher current signal that is capable of driving a motor.

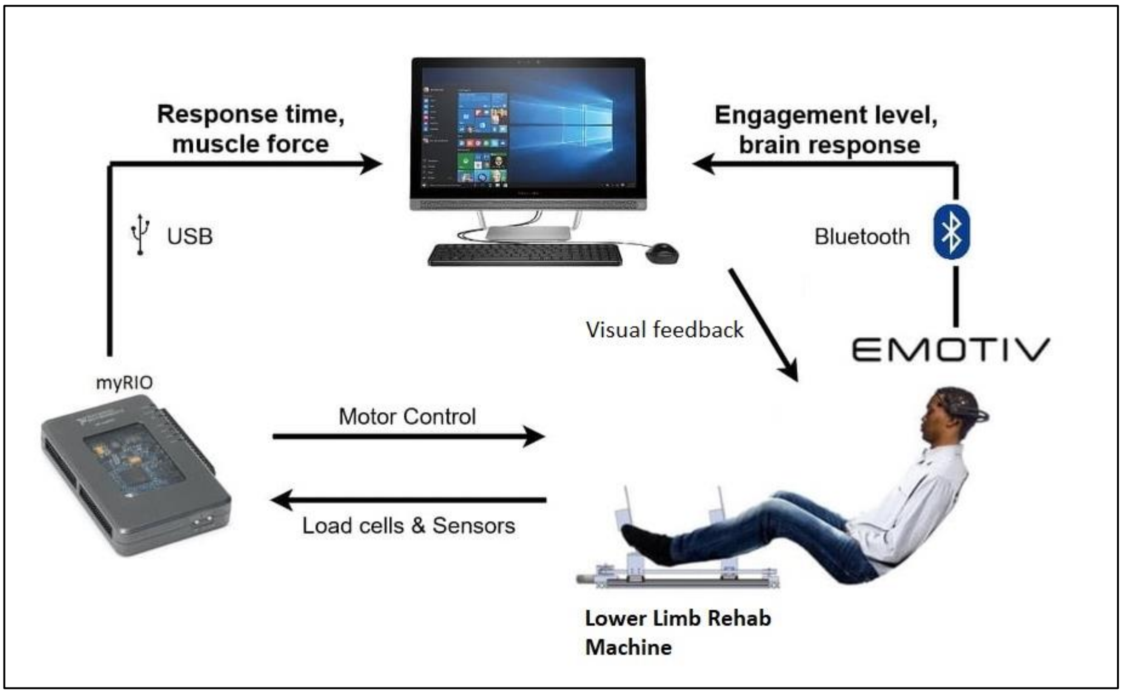

Figure 3-3: Overall system layout of Lower Limb Stroke Rehabilitation Machine. This figure only demonstrated the basic flow where the electronic components (e.g. motor driver) are not shown.

3.3 Training Modes of Lower-Limb Rehabilitation Machine

Sections below shows the flow chart of basic control modes designed which is Continuous Passive Motion (CPM) and Active Resistance Motion (ARM) training modes via LabVIEW algorithms.

3.1.1 Continuous Passive Motion (CPM)

CPM mode is specifically designed for stroke patients who lost their ability to control the movement of their lower limb, so the their movement will be passively moved driven by the motor. This training mode can help to promote motor recovery through the repetitive exercise and reduce muscle atrophy, but the patients will lack motivation. The flow chart is as shown in Figure 3-4.

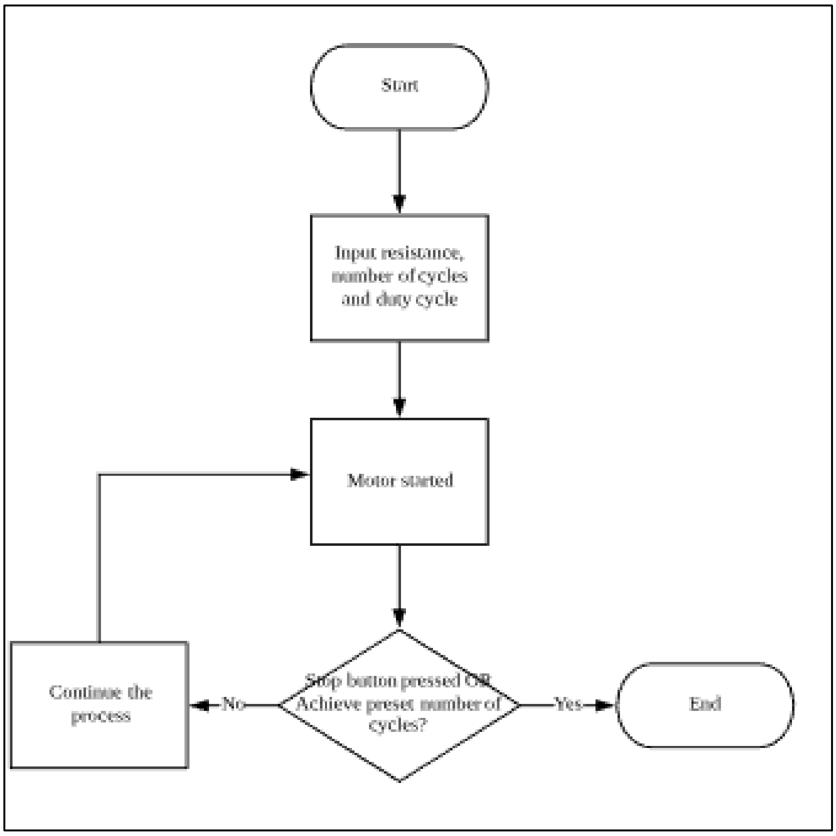

Figure 3-4: Flow chart of CPM mode

3.1.2 Active Resistance Motion (ARM)

ARM mode is designed for patients who have regained some motor function, and the preset resistance will improve muscle strength in patients by making the movement to be more challenging. In ARM mode, a preset and adjustable level of resistance is set in order to maximizing the patient's engagement by enabling the patients to achieve the desired motions only when the force applied exceeds the preset threshold value. The flow chart for ARM is as shown in Figure 3-5.

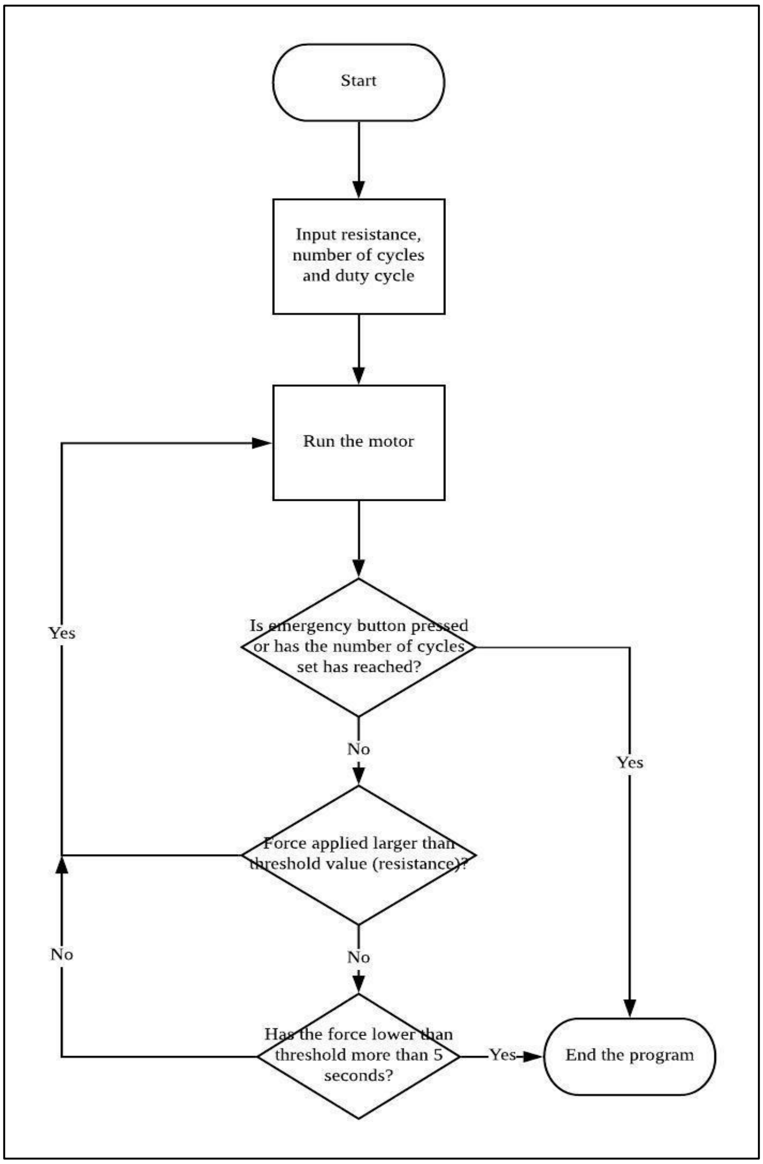

Figure 3-5: Flow chart of ARM mode

3.4 Error Augmentation Training Task

A target tracking-based challenge program was designed using LabVIEW algorithm. The program consisted of an experimental task involved in the tracking of a targeted indicator bar (left) that moved up and down repeatedly presented on a visual display (Figure 3-3) by controlling the force applied by the paretic legs with respect to a predefined threshold value. The force applied by the leg was transformed into the movement of an indicator bar (right) on the visual display: The controlled indicator bar (right) moved down when the force applied by the paretic leg is below the preset threshold, and up down when the force applied is above the preset threshold.

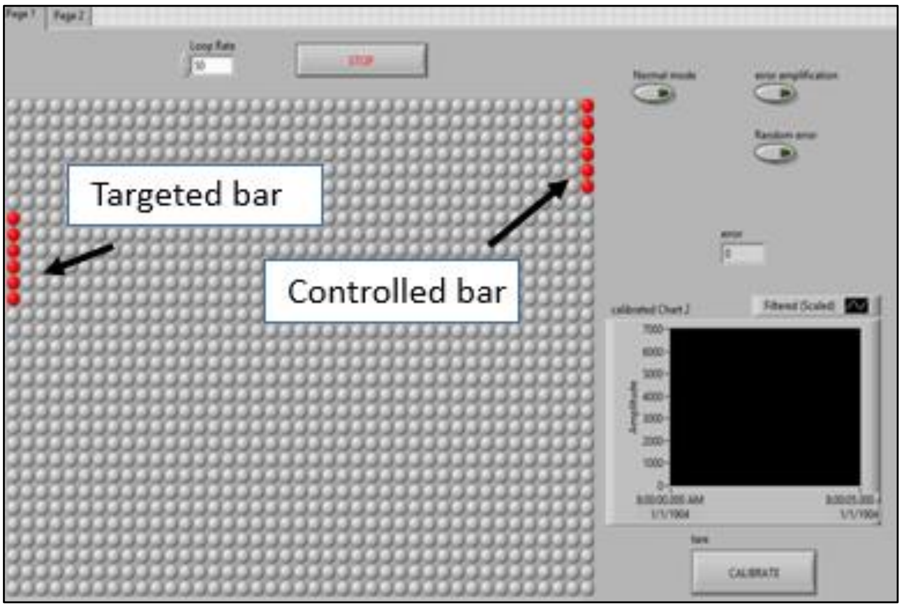

Figure 3-6: Target tracking-based challenge displayed on LabVIEW GUI. The indicator bar (right) is controlled by user based on the force applied by the leg to track targeted indicator bar (left) that moved up and down repeatedly.

3.4.1 Training Strategies

Subjects experience the experiment task with one of these training strategies: (i) Continuous Passive Motion (CPM) where passive assistance is provided from the driven motor without feedback, (ii) No perturbation (NP) where no force disturbances are presented, (iii) Error amplification (EA) where errors presented are amplified with a certain degree of repulsive forces, and (iv) Random force disturbance (RD) where random magnitude of force disturbances are induced. The repulsive force disturbance is induced by the changing speed of the motor, where higher motor speed represented lower repulsive force. The developed LabVIEW sub-VIs for all the robotic training strategies are covered in the Appendix. A brief summary regarding the training strategies is covered in the section below for completeness.

3.4.1(a) Continuous Passive Motion (CPM)

When the subjects are training with Continuous Passive Motion (CPM) model, the subjects’ legs will be passively driven by the motor without any means of interaction between the robot and their performance. This will be served as the interclass baseline for the experiment protocol (between the conventional method and challenged-based training strategies). The flowchart is shown in Figure 3-1.

3.4.1(b) No Perturbation (NP)

When subjects are training without perturbation, the subjects' are free from any force field disturbance when tracking the targeted bar during the rehabilitation exercise. Training without perturbation will be served as the intraclass baseline for the experiment protocol (between the three robotic training strategies: NP, EA, and RD). The flow chart for this NP training strategy is shown in Figure 3-7.

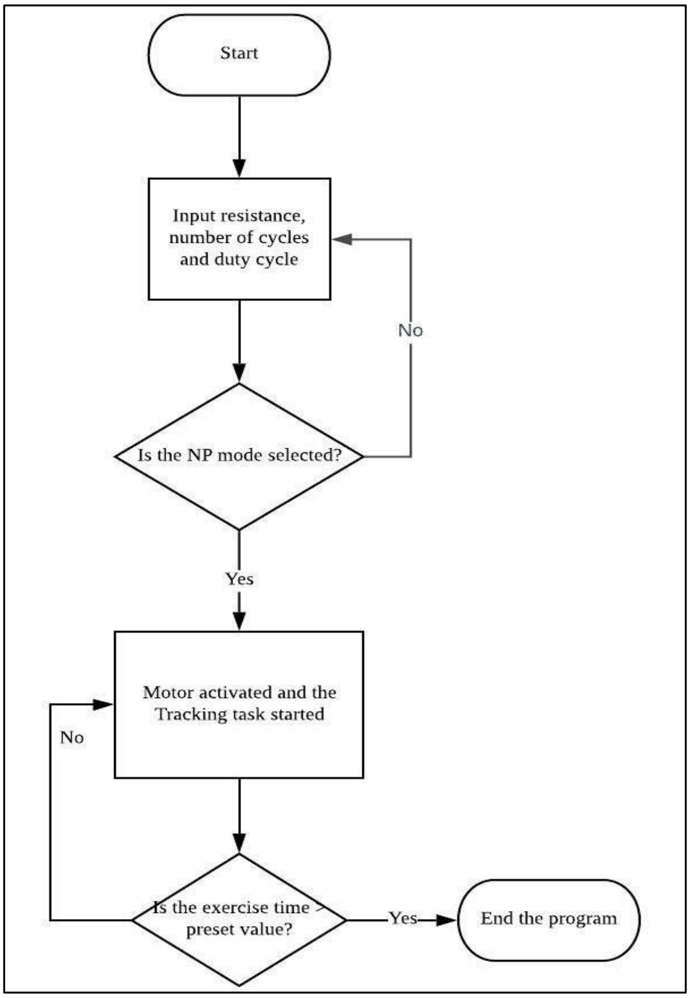

Figure 3-7: Flow chart of the no perturbations (NP) training strategy.

3.4.1(c) Error Amplification (EA)

The machine will increase the resistance based on the tracking error (differences between the position of the controlled indicator bar and targetted indicator bar) presented by means of repulsive force. The repulsive force will be induced as the tracking error increases to a magnitude larger than 5 unit and vice versa. The flow chart for this EA training strategy is shown in Figure 3-8.

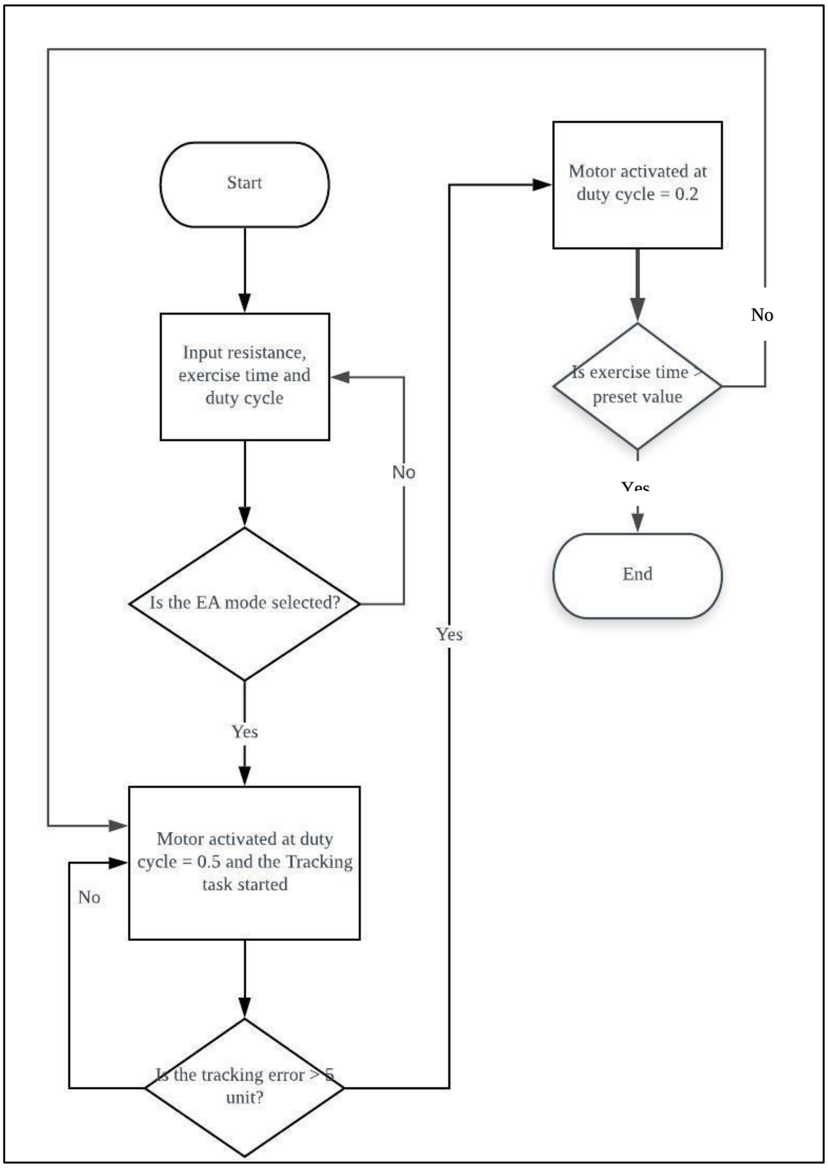

Figure 3-8: Flow chart of the error amplification (EA) training strategy.

3.4.1(d) Random Force Disturbance (RD)

The training strategy of random force disturbance is to force the patients to experience random perturbing forces during the tracking task. The machine applies unpredictable resistance by changing the speed using the motor. The motor applies a perturbing force that persists for about 2 seconds with a random duty cycle between 0.15, 0.3 and 0.5 for every 2-second interval. The flow chart for this RD training strategy is shown in Figure 3-9.

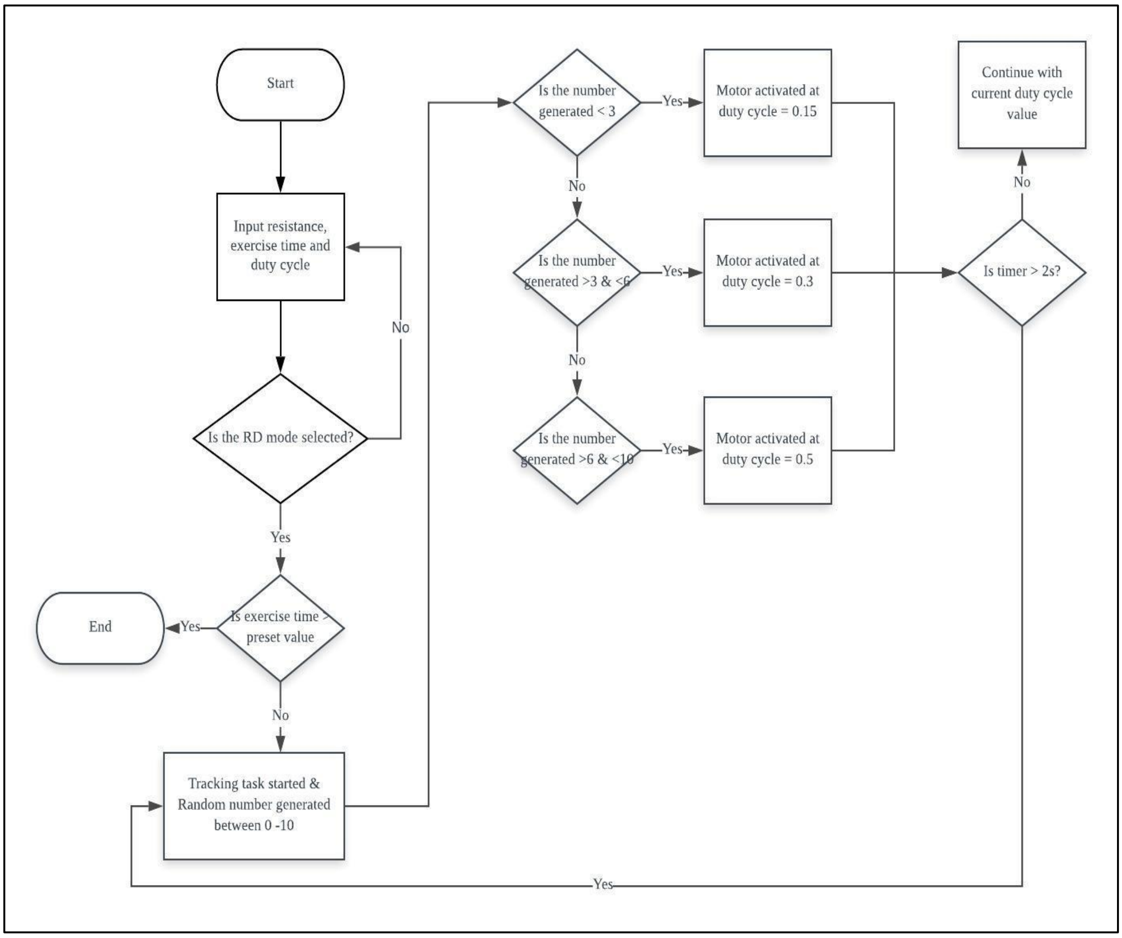

Figure 3-9: Flow chart of the Random Force Disturbance (RD) training strategy.