PERFORMANCE-BASED ADAPTIVE MODULATION OF RESISTANCE IN HAND REHABILITATION SYSTEM USING FINGER-EXTENSOR MECHANISM

BY

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INTERNATIONAL ISLAMIC UNIVERSITY MALAYSIA

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ABSTRACT

In robot-aided therapy, control algorithms provide minimal assistance to patients during therapy to encourage active participation from them. This is accomplished by triggering assistance based on patient participation. However, such control strategies fail to account for changes in patient performance within a single exercise session. This leads to a slacking response from the patient which impedes recovery. Furthermore, resistive therapy, which helps patients in regaining motor function more effectively has not been widely implemented in the area of hand rehabilitation. The objective of this research is to develop a performance-based impedance control algorithm for modulation of resistive force exerted on the patient during a single therapy session. First, the system model of the 1-DOF finger extensor rehabilitation machine was developed. Then a performance-based impedance control law was designed with the capability of using force exerted by the patient during therapy as a basis for modulation of resistive force applied by the machine on to the patient. Stiffness parameter of the controller and the consequent force applied on the patient was modulated with each change in patient performance, as measured by a Force Sensing Resistor (FSR). A Graphical User Interface was also developed to provide real-time feedback of patient performance. The system model developed in the first step was validated through simulation and hardware experimentation. Implementation of the control algorithm was carried out on the real system and resistive therapy experiments were performed with a healthy subject. Performance of the developed controller was evaluated by drawing a comparison between the reference force generated by the algorithm and actual force output on the subject during three resistive therapy sessions. Root Mean Squared Error of 0.9875 was obtained which shows that the developed mathematical model represents the real behaviour of the physical system closely. Mean absolute error over the three resistive therapy sessions between the reference force and the force exerted by the machine on the subject was found to be 0.843 N whereas the relative error was 3.72%. Based on the experimental results, it is proven that the developed control strategy is able to change the control parameter within a single therapy session and modulate resistive force exerted on the subject throughout the session. Hence, the controller is successful in avoiding slacking behaviour during therapy.

خلاصة البحث

في العلاج بمساعدة الروبوت الطبي، توفر خوارزميات التحكم الحد الأدنى من المساعدة للمرضى أثناء العلاج لحثِّ وتنشيط مشاركتهم، ويتم تحقيق ذلك من خلال إطلاق المساعدة على أساس مشاركة المريض. ومع ذلك، فإن استراتيجيات التحكم هذه تفشل في حساب التغييرات في أداء المريض خلال جلسة تمرين واحدة، وهذا يؤدي إلى تراخي استجابة المريض مما يعيق الشفاء. علاوة على ذلك، لم يتم تطبيق علاج مقاوم يساعد المرضى في استعادة الوظيفة الحركية بشكل أكثر فعالية على نطاق واسع في مجال إعادة تأهيل الإصبع أو اليد. يهدف هذا البحث إلى تطوير خوارزمية التحكم في المقاومة المعتمدة على الأداء لتعديل قوة المقاومة التي تمارس على المريض خلال جلسة علاج واحدة. أولاً: تم إجراء النمذجة الرياضية ومحاكاة النظام لجهاز إعادة تأهيل مُمَدّد العضلة DOF-1. ثم كانت وحدة تحكم المقاومة المعتمدة على الأداء مصممة بإمكانية استخدام القوة التي يبذلها المريض أثناء العلاج كأساس لتعديل قوة المقاومة التي تطبقها الآلة على المريض. تم تعديل صلابة وحدة التحكم وبالتالي القوة المطبقة على المريض لتناسب كل تغيير محتمل في أداء المريض ، كما تم قياسه بواسطة مقاومة استشعار القوة. تم تصميم واجهات المستخدم الرسومية أيضًا لتقديم ملاحظات في الوقت الفعلي عن أداء المريض. تم التحقق من صحة نموذج النظام الذي تم تطويره في الخطوة الأولى من خلال المحاكاة وتجريب الأجهزة. عرض جذر متوسط الخطأ التربيعي 0.9875 فكان قريبا من نموذج أداء النظام الحقيقي الطبيعي. تبع ذلك تنفيذ خوارزمية التحكم على النظام الحقيقي والتجريب على شخص سليم. ولتقييم أداء وحدة التحكم المطورة . تم إجراء مقارنة بين القوة المرجعية الناتجة عن الخوارزمية والقوة الفعلية قوة الإخراج على المريض خلال ثلاث جلسات علاج مقاوم. وجد أن متوسط الخطأ المطلق خلال هذه الجلسات بين القوة المرجعية والقوة التي تمارسها الآلة على الشخص يساوي 0.843 نيوتن ، بينما كان الخطأ النسبي يساوي 3.72٪. وبناءً على النتائج التجريبية ، تم التوصل إلى أن استراتيجية التحكم المطورة كانت قادرة على مراقبة أداء المريض خلال جلسة علاج واحدة وتعديل المقاومة المقدمة وفقًا لذلك.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion; it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science (Mechatronics Engineering) .

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DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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TABLE OF CONTENTS

Abstract ii
Abstract in Arabic iii
Approval Page iv
Declaration v
Copyright vi
Acknowledgements vii
List of Tables x
List of Figures xi
List of Symbols xiv
List of Abbreviations xv

CHAPTER 1: INTRODUCTION 1
1.1 Background 1
1.2 Problem Statement 3
1.3 Research Objectives 4
1.4 Research Methodology 5
1.5 Research Scope 6
1.6 Thesis Organization 8

CHAPTER 2: LITERATURE REVIEW 9
2.1 Introduction 9
2.2 Neuroplasticity and Motor Learning 11
2.3 Hand Rehabilitation Robots 12
2.3.1 Powered Hand Exoskeleton Devices 13
2.3.2 End-Effector Hand Rehabilitation Robots 16
2.4 Modelling of Rehabilitation Robots 19
2.5 Control Techniques for Rehabilitation Robots 20
2.5.1 Impedance Control 21
2.5.2 Assist-As-Needed Control (AAN) 23
2.5.3 Performance-Based Modulation of Assistance Using Impedance Control 27
2.6 Active-Resistive Therapy 32
2.7 GUI for Upper-Limb Rehabilitation Robots 33
2.8 Summary 37

CHAPTER 3: MODELLING, CONTROLLER FORMULATION AND GUI DEVELOPMENT 39
3.1 Introduction 39
3.2 Finger Extensor Rehabilitation Machine 39
3.3 Mathematical Model of Finger Extensor Machine 42
3.3.1 Mechanical Model 43
3.3.2 Actuator Model 46
3.3.3 Integrated Model for Finger Extensor Rehabilitation Machine 49

3.4 Performance-Based Impedance Control Algorithm Development .. 50
3.4.1 Performance-Based Resistive Force Modulation 56
3.5 Graphical User Interface (GUI).. 57
3.6 Experimental Set-Up 58
3.6.1 The Overall Finger Extensor Rehabilitation System......... 59
3.6.2 Sensory and Actuation System................................... 60
3.6.2.1 Position and Force Feedback......................... 60
3.6.2.2 Actuation System 61
3.6.3 Microcontroller 62
3.7 System Integration 62
3.7.1 Encoder Integration 66
3.7.2 Force Sensing Resistor Integration 67
3.8 Summary 68

CHAPTER 4: RESULTS AND DISCUSSION...................................... 70
4.1 Introduction... 70
4.2 Motor Parameter Determination for Model Validation................ 70
4.3 Model Validation 73
4.3.1 Simulation... 73
4.3.2 Hardware-In-The-Loop Experimental Set Up 77
4.3.3 Experimental Results for Model Validation.................... 78
4.4 Control Algorithm Implementation.. 80
4.5 Resistive Therapy Experiment 81
4.5.1 Experimental Results On Controller Implementation 82
4.6 Graphical User Interface.. 91
4.7 Summary 94

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS 96
5.1 Conclusion.. 96
5.2 Limitations of Study and Recommendations 98

REFERENCES 101

APPENDIX A: Arduino Code.. 106
APPENDIX B: Processing Code... 107

LIST OF TABLES

Table 2.1	Hand rehabilitation devices and notable features.	18
Table 2.2	Summary of the implementation of AAN control for rehabilitation robots.	26
Table 2.3	Implementation of performance-based, online modulated impedance control.	28
Table 3.1	Finger Extensor specifications.	41
Table 4.1	Motor parameters.	71

LIST OF FIGURES

Figure 1.1	Research Methodology	7
Figure 2.1	Post-stroke impairments of the upper-limb (American Association of Neurological Surgeons).	10
Figure 2.2	Gloreha and BRAVO hand exoskeletons (Medicalexpo.com; Leonardis et al.,2015).	13
Figure 2.3	MentorPro and WRES hand exoskeletons (hypepotamus.com; Buongiorno et al.,2018).	15
Figure 2.4	The AMADEO and CR2 devices in use. (Germanotta et al.,2020; Khor et al.,2014).	16
Figure 2.5	3 DOF IIT robot and the 2 DOF HapticKnob (Masia et al.,2009; Lambercy et al.,2007).	17
Figure 2.6	Performance-based impedance control for CP Walker robot (Fricke et al.,2019).	29
Figure 2.7	Performance-based impedance control of a wrist robot (Marini et al.,2019).	30
Figure 2.8	The three tasks, Snapping (left), Catching (centre), Ball Dropping (right) (Ocampo et al.,2019).	34
Figure 2.9	(A) Flying bird game. (B) Spaceship game. (C) Transferring virtual environment-simulated supermarket. (D) Transferring kitchen and cooking scenario (Huang et al.,2018).	35
Figure 2.10	Trajectory tacking and jigsaw puzzle GUIs.(Stroppa et al.,2018; Marini et al.,2017).	36
Figure 2.11	Haptic interface for CR2 robot and Tracing the digit 8 virtual environment (Khor et al.,2014; Vergaro et al.,2010).	36
Figure 3.1	1-DOF Finger Extensor machine (Ali, 2019).	40
Figure 3.2	CAD drawing of the side view of the iris mechanism (Ali, 2019).	41
Figure 3.3	Inner view of the machine.	42

Figure 3.4	Block diagram representation.	44
Figure 3.5	Forces acting on the mechanism.	44
Figure 3.6	Motor schematic (Osman, 1992).	47
Figure 3.7	Overview of the proposed performance-based impedance control for resistance modulation.	52
Figure 3.8	Flowchart illustrating modulation of resistive force.	57
Figure 3.9	Experimental set-up.	59
Figure 3.10	The finger extensor rehabilitation system.	60
Figure 3.11	Sensory system components.	61
Figure 3.12	Complete hardware set-up of the finger extensor rehabilitation system.	63
Figure 3.13	Performance-based impedance controller implementation in Simulink.	65
Figure 3.14	Encoder S-Function and associated blocks.	67
Figure 3.15	FSR calibration curve and placement on the device.	68
Figure 3.16	FSR integration blocks.	68
Figure 4.1	Motor characteristic curves.	72
Figure 4.2	Motor power-efficiency plot.	72
Figure 4.3	Overall system block diagram in Simulink.	74
Figure 4.4	Comparison between target and simulated angular position of the iris.	76
Figure 4.5	System simulation response to trajectory generator.	77
Figure 4.6	Velocity and acceleration during simulation.	77
Figure 4.7	Experimental setup for HiL simulation.	78
Figure 4.8	Simulated and experimental responses during open-close movements.	79

Figure 4.9 Simulated and experimental responses for target angle experiment. 80

Figure 4.10 Fully closed to fully open position of the poles of the finger extensor during experiments with healthy subject. 82

Figure 4.11 Force exerted by the subject f_{pat} during the resistive exercise, measured by the FSR. 83

Figure 4.12 Comparison of the target and the actual force exerted on the subject. 84

Figure 4.13 Change in position of the poles of the finger extensor. 84

Figure 4.14 (a) Force exerted by the subject during session 2; (b) the corresponding change in stiffness K. 86

Figure 4.15 Comparison of the target and the actual force exerted on the subject. 87

Figure 4.16 Change in position of the poles of the finger extensor. 88

Figure 4.17 (a) Force exerted by the subject during session 3 and (b) the corresponding change in stiffness K. 89

Figure 4.18 Comparison of the target and the actual force exerted on the subject. 90

Figure 4.19 Change in position of the poles of the finger extensor. 91

Figure 4.20 Three stages of 'save the egg' GUI. 92

Figure 4.21 Performance feedback GUI with patient's force within safe range. 93

Figure 4.22 Performance feedback GUI with patient's force exceeding safe range. 93

Figure 4.23 Stages of the GUI with respect to force exerted by the patient (f_{pat}). 94

LIST OF SYMBOLS

α	Parameter relating stiffness and force-tracking error
B	Damping of the robot (Nm/s)
$F(t)$	Reference force exerted on the patient (N)
f_d	Desired force by the patient (N)
$F_{machine}$	Force applied by the finger extensor machine (N)
f_{pat}	Force exerted by the patient (N)
K	Stiffness of the robot (Nm/rad)
k_0	Base stiffness of the robot (Nm/rad)
T_e	Force exerted by the patient (Nm)
T_g	Force applied on the patient (Nm)
$\theta(t)$	Angular position (°)
$\theta_d(t)$	Desired angular position (°)
$\dot{\theta}(t)$	Angular velocity (rad/s)
$\ddot{\theta}(t)$	Angular acceleration (rad.s^{-2})

LIST OF ABBREVIATIONS

AAN	Assist As Needed
ALEx	Arm Light Exoskeleton
CAD	Computer-Aided Design
ChARMin	Child Arm Rehabilitation Robot
CPR	Counts per Revolution
CR2	Compact Rehabilitation Robot
DOF	Degree of Freedom
EEG	Electroencephalography
EMF	Electromotive Force
EMG	Electromyography
FSR	Force Sensing Resistor
GUI	Graphical User Interface
HD2	High Definition Haptic Device
HEXORR	Hand Exoskeleton Rehabilitation Robot
HEXOSYS	Hand Exoskeleton System
HiL	Hardware in the Loop
HMI	Human Machine Interface
MATLAB	Matrix Laboratory
MBD	Model-Based Development
PID	Proportional–Integral–Derivative
PWM	Pulse Width Modulation
RBF	Radial Basis Function
RMSE	Root Mean Squared Error
RPM	Revolutions per Minute
sEMG	Surface-electromyography
VAEDA	Voice and Electromyography-driven Actuated
WRES	Wrist Exoskeleton

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Every year up to 15 million people suffer from stroke, making it one of the leading causes of severe disability in the world (Khor et al., 2014). After the initial stroke, survivors suffer from strong impairment of motor function that drastically affects their daily activities such as eating, manipulating objects, writing etc. Loss of the ability of carrying out basic acts of daily living makes them dependent on others. Hence, in order to improve their quality of life and increase their independence, physical rehabilitation becomes a necessity. Such rehabilitation is carried out in hospital centres using intense arm/hand training, electro-stimulation and/or drug treatment. The objective is to restore partial hand-function that will help stroke patients in performing acts of daily living. Studies have revealed that intense practice of repetitive movements can help improve the strength and use of the affected hand or arm (Lambercy et al., 2018).

Robots for rehabilitation purposes have gradually gained popularity and are redefining the current clinical strategies. Robot-assisted rehabilitation is more accurate and systematic as compared to conventional therapy. It has the ability of delivering intense and long duration repetitive sessions without the constant presence of a therapist. Thus, robot-aided therapies have the added advantage of removing complete dependence of patients on the therapist to some extent. This allows more exercise time per patient and also reduces the burden on the health care sector. Furthermore, rehabilitation robots can simulate interesting virtual environments through haptic displays making therapy sessions less monotonous. Such robots can also quantify progress achieved by patients and display motivational messages to keep them engaged. Therapy sessions can also be increased in complexity as patients make positive progress (Ferguson et al., 2020).

The aim of research in the area of rehabilitation robotics is to use technology to supplement clinical therapy and enhance its efforts in facilitating functional recovery of affected individuals. Depending upon the rehabilitation stage of the patient, robotic therapy can be passive, active-assistive, active and active-resistive (Krebs, 2018). A great portion of robotic rehabilitation literature lays emphasis on development of task specific and active-resistive therapy that encourages voluntary participation from patients thereby increasing their motor-plasticity. One of the most important steps towards achieving this goal is development of the most effective control algorithm. Effectiveness of the algorithm depends on: (a) Providing minimal robotic assistance to patients for completion of a task and encouraging active responses from them. (b) Tailoring therapy to the individual patients' needs and capabilities.

Based on these objectives many control strategies have been proposed and implemented, where patient performance has been taken into account in order to provide assistance. One of the prominent ones are the Assist-as-Needed (AAN) strategies. AAN control strategy evaluates the performance of patients using various performance parameters such as elapsed time, force generated, limb velocity, muscle activity to modulate the assistance provided during therapy. In the event that any of these parameters fall below a certain threshold, the controller intervenes and helps patients to complete the motion. The threshold is set based on the level of impairment of the patient.

However, this approach has some limitations: It is known to have caused a slacking response among patients, whereby they trigger assistance with their initial movement and then let the robot take over the entire session. Also, modulation of assistance takes place on a session-session basis and not in real-time. This is counter-productive to the efforts of encouraging patients to make voluntary movements during therapy (Emken et al., 2007).

Hence, the focus of this research is to overcome the above mentioned drawbacks prevalent in current control techniques and implement a performance-based impedance control strategy that is capable of modulating the resistive force within a single therapy session. This study aims to further the contribution towards development of effective controllers for robot-aided rehabilitation and counter drawbacks prevalent in current control schemes by tailoring therapy sessions to the needs and capabilities of individual patients.

1.2 PROBLEM STATEMENT

Active involvement of neurological patients in robot-aided rehabilitation plays a vital role towards the improvement of their motor function. AAN controllers developed for this purpose help the subject in task completion while keeping assistance provided to a minimum. These control algorithms trigger assistance only when a performance parameter falls below a threshold value and then continue assistance till the end of the exercise session.

The first problem in the research is that AAN control often leads to a slacking response from the patient where he/she triggers assistance and then lets the robot take-over the rest of the session. The second problem in the research is that AAN controllers fail to account for changes in performance within a single exercise session as assistance is modulated only on a session to session basis. Hence, there is no real-time monitoring and modulation of assistance which poses a danger of affecting patient progress over a course of time. The third problem is that resistive therapy, which helps patients in regaining motor function and strength has not been widely implemented in the area of finger/hand rehabilitation.

Therefore, a control scheme with the ability to modulate assistance/resistance in real-time based on the subject's performance is highly necessary. Such a control strategy will ensure the tailoring of therapy sessions to specific impairment levels of individual patients.

1.3 RESEARCH OBJECTIVES

1. To formulate a mathematical model for the finger extensor system for hand rehabilitation.

2. To develop a performance-based impedance control algorithm capable of online modulation of resistive force of the finger extensor rehabilitation machine.

3. To develop a Graphical User Interface (GUI) for the finger extensor rehabilitation machine to provide necessary motivation to patients during therapy.

4. To validate the proposed performance-based impedance controller through simulation and hardware experimentation.

1.4 RESEARCH METHODOLOGY

The methodology followed for achieving the above mentioned objectives is as follows:

Literature Review: In this step, an insight is gained into the work carried out by other researchers in the field of robotic rehabilitation. This step is vital to critically analyze work of others in the relevant field and determine the gaps in existing research. It also helps in realizing the scope of the research project and understanding the problem statement.

System Modelling: This is one of the most crucial steps in the development of a hand rehabilitation mechanism. System modelling of the finger extensor rehabilitation machine is performed using Lagrange-Euler method. The developed model is then validated through hardware experimentation.

Controller Development: In this step, a performance-based impedance controller is designed with the capability of online modulation of resistive force applied to the patient. This step involves identification of parameters of patient's performance and formulation of a stiffness adjustment algorithm. This step is realized through MATLAB (Matrix Laboratory) and Simulink software.

GUI Development: First, a user interface is designed keeping in mind ease of use and constraints. Then, a GUI is developed to complement the working of the hand rehabilitation mechanism in order to make it more motivating and engaging for long duration use with different types of exercises and a system of feedback for the patient.

System Integration: In this step, all the sub-systems namely the mechanical system, controller, GUI are integrated in order to create a complete rehabilitation system.

Testing and Evaluation: This step involves analyzing the performance of the performance-based impedance controller for online modulation of resistance through laboratory tests and experimentation and performing fine tuning.

The complete methodology is graphically represented as in Figure 1.1.

1.5 RESEARCH SCOPE

1. The scope of this research is hand rehabilitation only and does not cover the rehabilitation of other parts of the upper-limb such as the wrist, elbow, shoulder.

2. The focus of this research is on patients who possess or have regained basic functional ability in their fingers. Rehabilitation of patients who have lost complete motor function of the hand and fingers are beyond the scope of this research.

3. This research involves the utilization of a GUI and therefore the patients with visual or sound impairments are beyond the scope of this study.

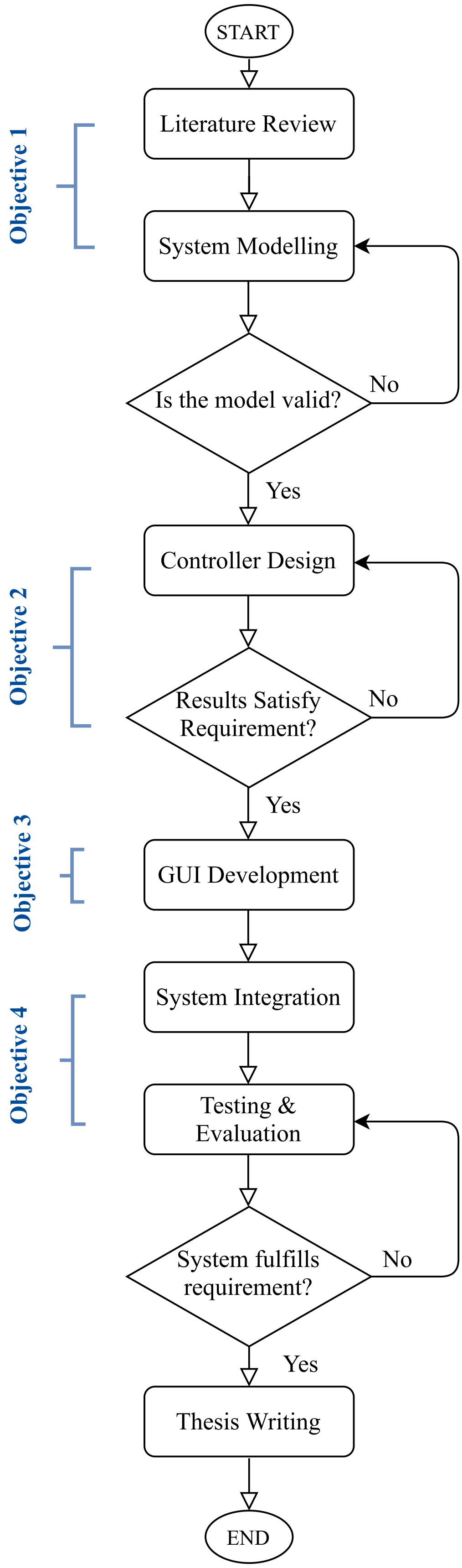

Figure 1.1: Research Methodology

1.6 THESIS ORGANIZATION

This thesis is organized into five chapters. Chapter One presents an introduction to the present work. It comprises of background of the problem, research foundations and concepts. This chapter states the problem statement, objectives, scope and methodology of research.

Chapter Two provides an extensive literature review on hand rehabilitation devices, the various control schemes implemented in the field of robot-aided rehabilitation, augmentation techniques utilized and various forms of therapy for individuals suffering from post-stroke impairments. Gaps in existing research are also identified and highlighted in this chapter.

Chapter Three describes system modelling of the rehabilitation device used in this study. This chapter explains the methods used towards determination of mechanical and electrical parameters used in the modelling process. The design and development of the performance-based impedance control algorithm is also explained. This is followed by development of the GUI.

In Chapter Four, the validation of the developed model through simulation and hardware experimentation is presented. The performance-based impedance controller is implemented through resistive exercises with a healthy subject and the results obtained are discussed. Performance of the GUI is also discussed in this chapter.

Chapter Five presents the conclusions drawn from the research. It sheds light on the limitations of the study as well as potential works that can be extended from this research.