Control System and Graphical User Interface Design of an Upper-Extremity Rehabilitation Robot

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Stroke is one of the leading causes of death, physical disability, and loss of brain functionality each year, especially amongst older adults [7]. The ability to access good quality post-stroke rehabilitation exercises is essential for stroke survivors to maximize their potential to regain skills and physical abilities. Robot-assisted therapy is showing promise as a way to provide stroke survivors with engaging, challenging and repetitive tasks while delivering measured therapy that is able to objectively evaluate patients' progress [65]. Among several challenges that are associated with the design of rehabilitation robots (e.g., the mechanical structure, the actuator types, the control strategies), the design of the control strategy is one of the most critical [6, 82, 131]. Depending on the type of patient and the severity of the impairment of motor control, various control strategies could be applied for the recovery of the impaired limb in stroke survivors using robot-assisted therapy [131]. Research is needed into the development of how best to control rehabilitation robots; this includes both the internal control algorithms and the User Interface (UI) for therapists.

As such, the first objective of this research is to design and implement a motion controller and force-field controller for a 2-Degree of Freedom (DOF) manipulandum upper-extremity rehabilitation robot that is able to deliver planar rehabilitation exercises for stroke survivors while taking therapeutic rehabilitation goals into account. The motion control algorithm can precisely follow a prescribed time-dependent trajectory whereas the force-control method will only provide assistance (or even resistance to introduce extra challenge) to the patient to do the task rather than forcing the movement. For doing the simulation studies, a motor control model of post-stroke patients was proposed. The

effectiveness of these controllers was explored in simulations and it was observed that the developed force-field algorithm had a positive effect on the motor control recovery for a simulated patient. The simulation results also indicated that the resistive mode of therapy would result in better outcomes after the therapy which aligns with experimental studies by other researchers [38,96]. In addition, a novel adaptive algorithm was proposed for fine-tuning the proposed force-field parameters based on the performance of the patient during the therapy as a subject specific controller can help to achieve a desirable performance for each patient [113]. While this approach is promising, the effectiveness of the adaptation rule has yet to be evaluated on real patients in the future.

To enable effective access and use of the robot, the controller needs to be visualized through a Graphical User Interface (GUI) in a way that therapists can understand and use. The second goal of this thesis research was to work with therapists to collaboratively design an intuitive to use GUI for therapists to control the robot and provide objective information on patients' performance. The identification of features and feedback on the intuitiveness of the GUI developed in this research highlights the value of collaborative design between engineers and therapists to create the interface that enables therapists to control the rehabilitation robot. This research also identifies the need for collaborative GUI design with patients as their needs and preference may be different from therapists. During the collaborative GUI design, it was observed that including obstacles and force-field method might be a possible useful method for supporting patients' movement trajectory, not only because therapists can adjust the force strength to suit a specific patient, but also because they can use its numerical data for objective measurement of patients' performance. Therapists who participated in this research stated that objective measurements (i.e., trajectory smoothness, speed, mobility range and error) could be used to evaluate the patient performance. While rehabilitation robots are different in terms of mechanical structure, work-space, and the exercise that they can provide, similar methods could be used for supporting patients' movement trajectory and performance evaluation. As the GUI is the first prototype, it needs to be used with and evaluated by therapists and patients to ascertain if the information presented in the GUI is intuitive and to explore if they can understand it or use it.

Acknowledgements

This research would not have been possible without the kind support of many people and on the very top of the list, my wonderful supervisors, Dr. Jennifer Boger and Dr. John McPhee. I would like to express my deepest appreciation to Dr. Jennifer Boger for providing me with unfailing support and continuous encouragement throughout the two years of my Master's study. I would like to thank her for her patience and her great insights during this time. She thought me be to be a better engineer and a better problem solver by applying my knowledge to real-world problems. I am truly grateful for her invaluable guidance.

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Last but not least, I must express my very profound gratitude to my parents, whose love and guidance are with me in whatever I pursue. This accomplishment would not have been possible without their kind support.

Dedication

This is dedicated to my parents. For their endless love, support, encouragement, and most important of all for always believing in me.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ADL Activities of Daily Living

DOF Degree of Freedom

FMA Fugl-Meyer Assessment

GUI Graphical User Interface

UI User Interface

Chapter 1

Introduction

1.1 Motivation and Research Objectives

Stroke is one of the leading causes of death, physical disability, and loss of brain functionality each year, especially amongst older adults [7]. Good access to post-stroke rehabilitation exercises is essential for stroke survivors to maximize their potential to regain skills and physical abilities. However, a lack of availability of equipment and therapists can cause challenges in accessing rehabilitation exercises [2, 7]. In recent years, there has been substantial research in the use of robotic systems for rehabilitation purposes to augment conventional rehabilitation programs, such as leveraging robots' high precision and endurance [2, 37, 101, 132]. Rehabilitation using robot-assisted therapy has been shown to be effective in some situations for providing engaging, challenging, and repetitive tasks for stroke patients while reducing therapists' physical engagement and minimizing related costs [43, 65]. Rehabilitation robots show promise as a way to support clinicians' goal of providing patients with access to exercises that facilitate recovery as well as providing a more objective way to evaluate patients' progress [65].

In order to interact with robot-assisted therapy, therapists need to have access to a User Interface (UI). UI is a way that enables human users to interact with hardware (e.g., a computer or a robot) and software (e.g., a website or application). Making the user's experience easy and intuitive is the key goal of an effective UI. In order to receive the maximum desired outcome, the minimum effort should be required on the user's part [100, 112].

A graphical user interface GUI is a form of UI that allows people to interact with electronic devices through graphical icons [100]. The user interface is an essential aspect of the potential usability of robot-assisted therapy in rehabilitation. A good interface can facilitate user-robot interaction during the treatment session (and a bad one prevent it) [60]. While research related to robot-assisted therapy is growing, UI and GUI development (particularly those with end-user involvement) has not received much attention [59, 73]. By involving therapists in the design of the GUI, it is anticipated that their wants and needs will be better reflected in a design that enables them to the control the robot in a useful and intuitive way.

1.1.1 Objective and guiding research questions

The research presented in this thesis focuses on two aspects of an upper-limb rehabilitation robot control: 1) the design and development of different controllers for a planar 2 DOF robot; and 2) the design and evaluation of a proposed GUI for therapists to control it. Therefore the goals of this thesis are: 1) to propose a novel controller and a subject-specific algorithm, using force-fields method to find the adaptive force-field for a given patient, considering their performance over time, and 2) design a GUI that therapists could use to intuitively control the robot in the ways they would wish to and to provide objective information on patients' performance.

The two research questions guiding this thesis are:

1. How can control strategies be designed for robot-assisted therapy to address various training mode of therapy (i.e., active and passive) that are used for wide range of stroke patients with different impairment?
2. How can a GUI be collaboratively designed to enable intuitive control of the robot by rehabilitation therapists and provide objective information on patients' performance?

1.2 Structure of thesis

The remainder of the thesis is structured as follows:

Chapter 2 provides an overview of the literature, with a focus on two aspects related to the upper Extremity Robot-Assisted Therapy. First, there is an introduction to stroke and why there is a need for robot-assisted therapy, second is an overview of upper-limb rehabilitation robots.

In Chapter 3, as shown in flowchart summery of the thesis Fig. 1.1, first, an overview of

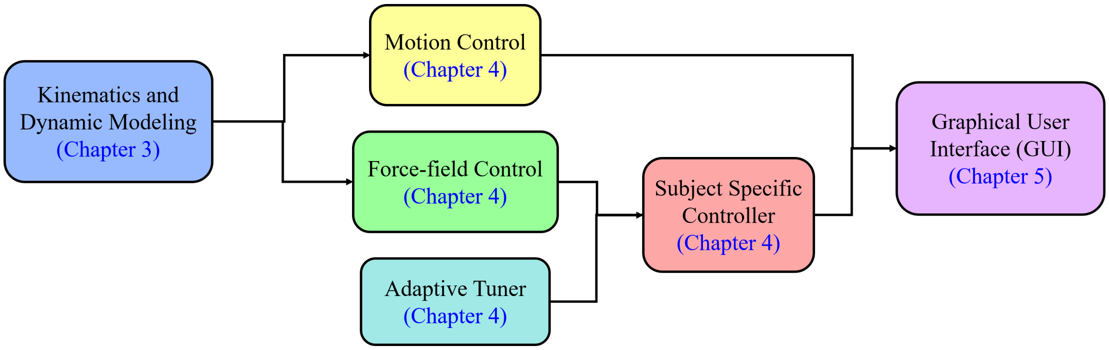

Figure 1.1: The flowchart summery of this thesis

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the robot system is given, focusing on its mechanical design and computer software. Then, the kinematic and dynamic models of the robot are presented.

In Chapter 4, the robot's controller is explained, two control strategies, namely, motion and force-field control, was designed to control the rehabilitation robot. In addition, a novel adaptive algorithm was proposed for fine-tuning the proposed force-field parameters based on the performance of the patient during the therapy.

Chapter 5 focuses on the collaborative development of GUI for therapists to control the robot. This was done through two iterations of interviews with rehabilitation therapists and design revisions.

Chapter 6 summarizes the key findings and conclusions as well as provides insights regarding future work related to the robot's controller and its GUI.

Chapter 2

Background and Literature Review

2.1 Stroke and Post-Stroke Rehabilitation

Stroke or Cerebrovascular disease is a sudden disturbance of the blood supply to the brain tissue; it is one of the leading causes of death, physical disability, and loss of brain functionality each year, especially amongst older adults [7]. It is stated that approximately 15 million people around the world have a stroke each year [107]. Of these, around five million individuals die, five million have a complete recovery, and another five million have permanent disability [107]. Stroke is the cause of a significant economic load, ranging from 2% to 4% of total healthcare costs worldwide for stroke-related medical costs and disability [91].

In the literature, it is stated that stroke patients experience difficulties in performing Activities of Daily Living (ADL) [19], motor functionality, paralysis, weakness, impaired balance, and loss of sensation, as well as significant reductions in body strength [71,80,103]. Post-stroke rehabilitation [1] is essential for stroke patients to regain some or all of the skills and physical functions that they had before stroke [34].

Upper-limb rehabilitation is crucial during the first six months after stroke, since after that, 33-66% of stroke survivors will experience a significantly reduction in the effectiveness of recovering upper-limb functionality [23, 66] The reduction in the functional recovery effectiveness after six months of stroke has been attributed to dynamic changes in the brain that occur post-stroke (both physiological and experience dependent) [29]. Stroke recovery can be impacted by many factors, such as the patient's age, motivation, and medical condition, the severity of the initial impairment, and the quality of and access to rehabilitation sessions [58]. Conventional rehabilitation programs usually require the supervision of therapists in fully or partially assisting patients for hand or arm joints movements, a process that is time-consuming and labor-intensive [23, 98].

2.2 Robot-assisted therapy

In the clinical setting, sensory and motor recovery, activity increase, assessment improvement, and assistance provided are the goals of therapy [39, 42, 65]. While the acute care of stroke patients has been improved remarkably, rehabilitation therapy in the last 75 years of practice has had limited advances for stroke survivors [65]. As the aging population grows, the demand for rehabilitation services and caregivers is increasing quickly and cur-

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[1] Post stroke rehabilitation is a process of engaging in tasks to improve motor, sensory, and cognitive function as well as being able to perform the ADL independently [46]

rent rehabilitation practices can be impractical in some certain tasks [65]. Approximately, 36-42% of people who have experienced stroke have a noticeable disability or are dependent on their caregivers for performing ADL after five years of stroke [47, 48]. Moreover, due to the lack of availability of equipment and therapists, access to rehabilitation exercises can also be very challenging for stroke survivors [77]. As a result of this situation, new approaches are needed to enhance the efficacy and productivity of rehabilitation. This demand has created an opportunity for technologies such as robotics to support both patients and therapists in the recovery process.

Robot-assisted therapy is utilizing robotic devices to rehabilitate post-stroke survivors and to deliver motor and task-oriented training [20]. In some cases, less supervision and independent training can often be performed, and patients are able to receive objective feedback on their performance and to get motivated using interactive games [51, 67].

Robot-assisted therapy falls into two main categories: robots that are designed to compensate for skills that have been lost, including self-feeding, mobility, or manipulation [110, 118] and the robots that are developed to support relearning motor function [33]; this thesis focuses on the latter.

Studies began with the MIT-Manus in the mid-1990s robot to determine whether intensive therapy using rehabilitation robots could be effective in reducing motor impairment post stroke. In a pioneering pilot study, Asien et al. [3] investigated motor impairment improvement in stroke patients using the MIT-Manus robot. 20 patients who were in their very first weeks after having a stroke received conventional therapy from therapists. The patients were randomly put into two groups. One of the groups was the robot treatment group, in which patients received an additional reaching tasks movement program from the robot for five days per week and one hour per day. The robot helped patients just like therapists when they could not reach to target. While patients in the other group, the robot exposure group, received the same task one hour/ per week throughout inpatient hospitalization, but when they required help the technician helped them and the robot did not assist the patients. As a result, patients in the first group (the robot treatment group) obtained considerable gains in the movement of both the elbow and shoulder of the paretic arm and strength, which were measured by the Medical Research Council (MRC) Motor Power test and the Motor Status Score. The results indicated that the more therapy was better and the robot had not adverse effect on patient, they also concluded that the robot may have the potential positive effect on the outcome [3, 35, 126]. In addition, the improvement after stroke for the patient in that group went through for up to 3 years [127].

In another study by Lum et al. [78] that compared robotic therapy and conventional therapy, all patients (n=27) went through 24 one-hour sessions during the period of two months and they supervised by a single occupational therapist. Patients were classified into two groups: 1) a robot group, in which patients received elbow and shoulder exercise from a robotic device; and 2) a control group, which was exposed to the robot for 5 minutes every session and went through conventional treatment. Researchers have found higher improvements in the proximal movement, strength, and reach extent on the Fugl-Meyer Assessment (FMA) test in the robot group after two months of treatment. However, after six months of treatment, no difference was found in both groups.

The positive effects of robot-assisted therapy on improving the motor control and the strength of a paretic arm, muscle, and arm function compared to conventional therapy

(a) Manipulandom upper-limb rehabilitation robot (end-efector based robot) used in this research

(b) Armeo Spring (exoskeleton robot), reproduced with the permission from [16]

Figure 2.1: Examples of an end-effector based robot and an exoskeleton robot

have recently been suggested in systematic reviews [84, 124]. When dose of usual care matched with robot assisted therapy, no significant difference were found in abilities in performing basic ADL and motor control and the benefits of robot-assisted therapy were not apparent. [67, 90]. However, other studies suggested that using robot-assisted therapy combined with usual care is more effective in terms of improving upper-limb motor function and control, muscle strength/tone and basic ADL rather than using robot-assisted therapy alone [14, 84, 124, 134].

2.2.1 Upper extremity rehabilitation robot structure

Upper extremity rehabilitation robots can be classified as [79, 89]:

1. **End-effector-based robot:** End-effector[2] robots are attached to the patients at one distal point, and their joints do not equal to those of human joints [54, 76, 79].
2. **Exoskeletons:** Exoskeleton robots are similar to human limbs and they are attached to patients' limbs at several points. Their joint axes usually equal to those of human joints [76]. Unlike the end-effector robots, these robots can provide movements to certain joints [42].

Usually, end-effector-based robots have simpler structure, and less complex control algorithms compared to the exoskeleton robot. However, it is difficult to perform a special movements of a particular joint in end-effector robots, since the positions of other joints will be changed simultaneously by the generated force at the distal interface [54, 76, 79]. End-effector robots at most can provide six DOF. "MIT-Manus", "InMotion2", "InMotion Arm" and "ReoGo" are commercially available end-effector robots [42]. On the other hand, the setup in exoskeleton robots is difficult, as they usually have many modules and due to the complexity of exoskeleton robots, it often takes more time for patients to adapt to the exoskeleton robot compared to the end-effector-based robots [104]. "ArmeoPower" and "ArmeoSpring" are commercial exoskeletons [130].

A recent randomized controlled trial study [72] has directly compared end-effector and exoskeleton robots in 38 chronic stroke patients with moderate to severe upper limb disability. Stroke patients were equally divided into the end-effector group using the "InMotion2" robot and exoskeleton group using the "Armeo Power" robot. They received a total of 20 sessions, (30 minutes of active therapy, five days a week for four weeks) along with the

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[2] End-effector is the device at the end of a robotic arm, which is designed to interact with the environment.

conventional occupational therapy, a total of 20 30-minutes-sessions. The study found the end-effector robot intervention was better than the exoskeleton robot intervention with regards to the activity and participation measured by WMFT score for activity, and stroke impact scale (SIS) for participation.

In addition to the difference in the mechanical characteristics of the end-effector and exoskeleton robots, several reasons may be associated with better outcomes in the end-effector group than in the exoskeleton group. The gravity support difference between the two robots might be a factor that affected the results, since the end-effector robot compensate for gravity and it operates in two-dimensional horizontal plane whereas the exoskeleton robot operates in three-dimensional space and it involves movements against gravity . Considering that the stroke participants in this study had moderate to severe motor disability, there might be a possibility that the interaction was challenging with the six DOF exoskeleton in three-dimensional space . It should be kept in mind that this was one study so results may be different for different robots and/or stroke populations.

2.3 Robot Control

The design of the control strategy is one of the most critical design criteria in rehabilitation robots [6, 82, 131]. Depending on the type of patient and the severity of the impairment of motor control, various control strategies could be applied For the recovery of impaired limb in stroke survivors using robot-assisted therapy [131].

In the initial stages of rehabilitation using rehabilitation robots, the aim is to increase the mobility range and to reduce the spasticity of the impaired limb [131]. In this stage, the robot should be controlled to guide the patient to follow a desired trajectory smoothly [6, 131]. Motion control (trajectory tracking) is one of the early controllers designed for the passive mode of training, which often aims to accurately follow the desired trajectory within the work-space of the robot [6, 62] without considering the effort of the patient. Proportional-integral-derivative (PID) feedback controller is the simplest control that usually is investigated for motion control [99]. Marcia et al. [92] controlled a RiceWrist to have a motion control using the traditional fixed gain PD (proportional-derivative) controller and found that the performance of this controller is dependent on of its proper PD gains selection and for different configurations, the performance could vary substantially. Most of the motion controllers have been designed for exoskeleton [41,125] and the problem with motion controllers is usually tuning its control parameters. In this thesis, a motion controller using PD-feed forward controller is proposed for a manipulandum rehabilitation robot to make the tuning process of the controller gains easier to work well within the whole work-space of the robot.

After passive rehabilitation training, patients usually needs to be engaged in the exercise and do active training, as they usually have partial control on their limb [6, 131]. For these individuals, an Assist-As-Needed controller could lead to promising outcome [128, 129]. This controller provides minimal assistance and it aims to engage the patients to complete the task [6, 97]. Recent assist-as-needed controllers were implemented using the force-field control methods [6,113]. Most of these controllers usually cannot be tuned to suit a specific patient due to their fixed set of control parameters [9, 74, 113]. Subject specific controller can help to achieve a desirable performance for each patient [113]. In this research, two novel force-fields are introduced and implemented as a possible method for motor control recovery of stroke patients followed by proposing a novel adaptive algorithm to fine tuning the control parameters.

2.4 Discussion and Conclusion

This chapter presented an overview of upper limb rehabilitation robots, including their mechanical structure and impact on stroke rehabilitation. While several studies have suggested the advantages of rehabilitation using robots, there is no decisive evidence that robot-assisted therapy has more benefits over the conventional therapy. In addition to the structural difference of rehabilitation robots, the way that the robots are included and used in the rehabilitation program as well as factors related to motor (re)learning likely play a role in the robot assisted therapy outcomes, however there is not yet enough data to understand these relationships [23]. Recently, other researchers [72, 95] have stated that significant functional outcome can possibly be achieved from the use of end-effector-based and exoskeleton rehabilitation robots, however, the results were different in those robots; this may be an indication that the intrinsic characteristics of the robots, including the structural difference, the type of robot's control structure or robotic actuation can cause these differential effects and affect the rehabilitation outcome [28, 83]. There is a lack of studies regarding the certain guidelines or standard requirements addressing the most suitable robot subcategory, degree of freedom extension, control strategies, the user interface. If such guidelines are understood, more suitable rehabilitation robots may be created to assist therapists and patients in post-stroke rehabilitation [72, 95]. This literature review suggests work needs to be done in the development of controllers for rehabilitation robots; both the internal control algorithms and the user interface for therapists. As such, this thesis research focuses on two design aspects of an upper-limb rehabilitation robot: 1) software/mechanical control strategy and 2) the design of the robot's GUI. In the next chapter, the system model of the robot will be discussed, which will be followed by the design of its controller.

Chapter 3

System Models: Upper Extremity Rehabilitation Robot

3.1 Overview of the End-effector Robot

Upper extremity rehabilitation robots are designed for home or clinical use [42, 89]. Based on their functionality, in the clinical setting, rehabilitation robots can provide two main types of therapy [6, 42, 109]:

1. Passive recovery training: In this mode of training, the robot move the patients' hand regardless of the patient's contribution [13, 44]. Passive recovery training usually happens in the initial stage of rehabilitation and it aims to increase the mobility range, and stimulate motor spasticity [87, 109]. This mode of therapy could be more beneficial for patients with severe impairment; however, it is stated to be less effective

for mildly impaired patients. This might be a possible issue with some robot devices that simply guide the participant and absolve the participant from doing the work.

2. Active recovery training: In this mode of training, the patient is actively engaged in the exercise. This mode of therapy could be suitable for patients with mild or moderate impairment and sufficient muscle strength [6, 22]. This mode of therapy aims to enhance motor learning and can be classified into two main types of (1) assistive and (2) resistive, based on the motor ability of patients [22]. In the assistive mode, the robot will assist the patient to accomplish the task whereas in the resistive mode, the robot makes the task challenging for the patient [44].

The manipulandum upper extremity rehabilitation robot that was used in this research (Fig 3.1) was designed and developed by Quanser Consulting Inc., the Toronto Rehab Institute (TRI) and the Motion Research Group (MORG) at the University of Waterloo. By performing repetitive reaching movements, the robot have the potential to help post-stroke patients to recover their range of motion and strength in the upper limb [42]. In this chapter, an overview of the robot system is given, focusing on its mechanical design and computer software. Then, the kinematic and dynamic models of the robot are presented before discussing how the derived model was verified by conducting a simulation study. The chapter closes with key findings and concluding thoughts.

3.1.1 Mechanical design

The manipulandum robot used in this research is a 2 DOF parallelogram mechanism that operates in the horizontal plane (see Fig. 3.1). Two DC motors with optical encoders

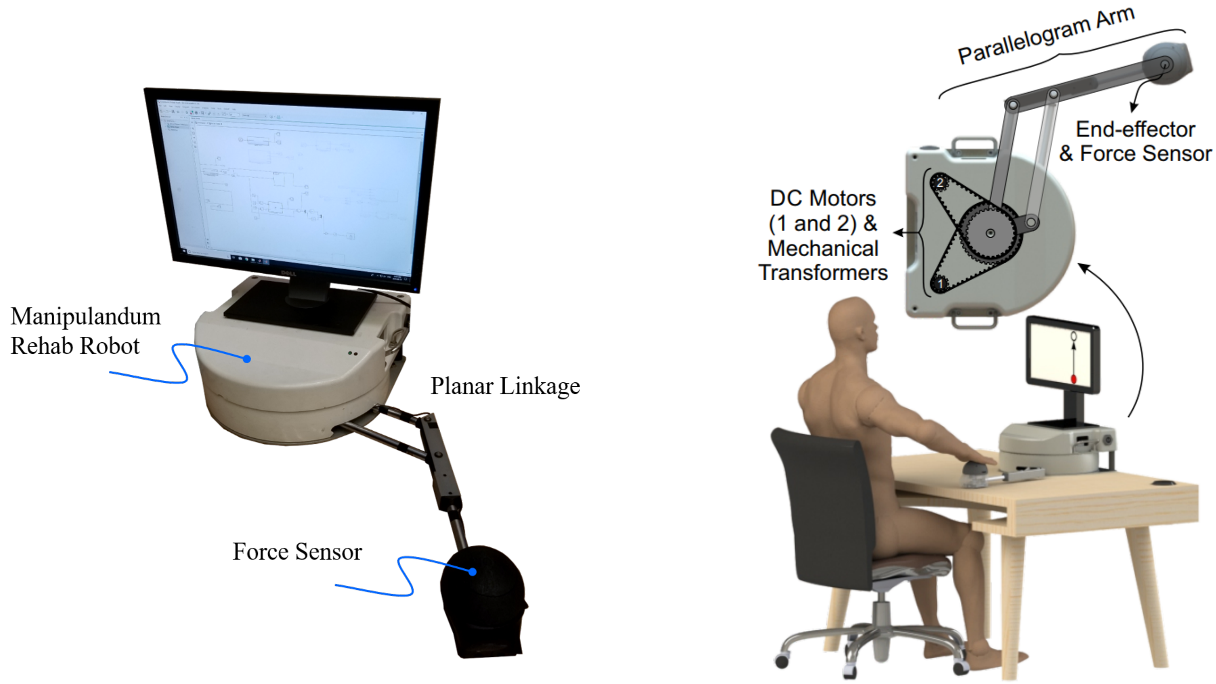


Figure 3.1: Manipulandum robot at Motion Research Group, University of Waterloo [42].

are connected to the parallelogram arm through two disc-and-timing-belt mechanisms [42] (Fig. 3.1).

The outer arm is connected to an end-effector where the handholds are mounted. The length of the links determines the work-space of the robot. The end-effector has a 6-axis Force/Torque (F/T) sensor (ATI Industrial Automation F/T Sensor: Nano25) that measures the interaction force between the robot and user (see Fig. 3.1) [42].

3.1.2 Computer Software

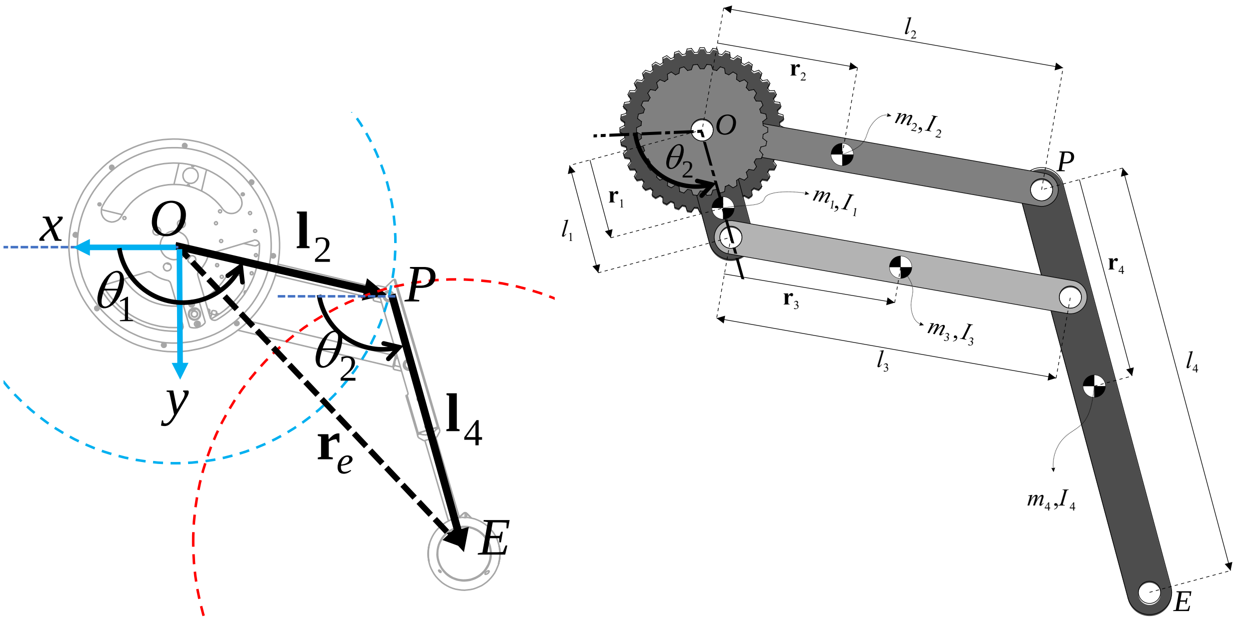
The interface of robot's computer software includes Simulink/MATLAB which integrates Quanser's real-time control software (QUARC). Communication between the driver and the application software is possible through TCP/IP and shared memory protocol. A National Instruments DAQ card (PCI-6229) is used for reading the F/T sensor data. The QUARC software supports and runs this DAQ card [42].

3.2 Inverse Kinematic Modeling

As a prerequisite for dynamic modeling and control implementation [123] (which are discussed in Chapter 4), the inverse kinematics equations for the position, velocity, and acceleration of different joints of the manipulandum are derived with respect to the position, velocity, and acceleration of the end-effector.

3.2.1 Position analysis

Figure 3.2 (a) depicts the top view of the robot. It should be noted that even though the second actuator is not connected to the joint P where θ_2 is shown, due to the existence of a parallelogram the angular displacements can be easily verified to be the same. Referring back to Fig. 3.2(a), position of the point P can be obtained by calculating the intersection of two circles with origins O and E with radius of l_2 and l_4 respectively. l_i denotes the



(a) Kinematic parameters. (b) Inertia parameters. This figure is adapted from [42].

Figure 3.2: The kinematic and inertia parameters of the manipulandom.

length of the ith link. As shown in [5], the solution to this problem yields:

$$\begin{aligned}\mathbf{l}_2 = &\left(\|\mathbf{r}_e\|^2 + {l_2}^2 - {l_4}^2\right)\frac{\mathbf{r}_e}{2\|\mathbf{r}_e\|^2} \\ &+ \sqrt{\left(\|\mathbf{r}_e\| + l_2 + l_4\right)\left(-\|\mathbf{r}_e\| + l_2 + l_4\right)\left(\|\mathbf{r}_e\| - l_2 + l_4\right)\left(\|\mathbf{r}_e\| + l_2 - l_4\right)}\left(\frac{\hat{\mathbf{k}} \times \mathbf{r}_e}{2\|\mathbf{r}_e\|^2}\right)\end{aligned} \tag{3.1}$$

$$\begin{aligned}\mathbf{l}_4 = &\left(\|\mathbf{r}_e\|^2 + {l_4}^2 - {l_2}^2\right)\frac{\mathbf{r}_e}{2\|\mathbf{r}_e\|^2} \\ &- \sqrt{\left(\|\mathbf{r}_e\| + l_2 + l_4\right)\left(-\|\mathbf{r}_e\| + l_2 + l_4\right)\left(\|\mathbf{r}_e\| - l_2 + l_4\right)\left(\|\mathbf{r}_e\| + l_2 - l_4\right)}\left(\frac{\hat{\mathbf{k}} \times \mathbf{r}_e}{2\|\mathbf{r}_e\|^2}\right)\end{aligned} \tag{3.2}$$

where $\hat{\mathbf{k}}$ denotes a unit vector along z-axis, and $\mathbf{r_e}$ is the position of the end-effector.

After obtaining $\mathbf{l}_2$ and $\mathbf{l}_4$ the actuated joint angles can be obtained as:

$$\theta_1 = \arctan\left(\mathbf{l}_2.\hat{\mathbf{j}}/\mathbf{l}_2.\hat{\mathbf{i}}\right) \tag{3.3}$$

$$\theta_2 = \arctan\left(\mathbf{l}_4.\hat{\mathbf{j}}/\mathbf{l}_4.\hat{\mathbf{i}}\right) \tag{3.4}$$

where $\hat{\mathbf{i}}$ and $\hat{\mathbf{j}}$ are the unit vectors along x- and y-axis.

3.2.2 Velocity Analysis

Input-Output Jacobian

The position of the end-effector could be written as:

$$\mathbf{r}_e = \mathbf{l}_2 + \mathbf{l}_4 \tag{3.5}$$

By taking the time-derivative of Eq. (3.5), the end-effector velocity, $\mathbf{v}_e$ can be obtained as:

$$\mathbf{v}_e = \dot{\theta}_1 \hat{\mathbf{k}} \times \mathbf{l}_2 + \dot{\theta}_2 \hat{\mathbf{k}} \times \mathbf{l}_4 \tag{3.6}$$

where Equation (3.6) can be rewritten as:

$$\mathbf{v}_e = \boldsymbol{\mathcal{J}}_e \dot{\boldsymbol{\theta}} \tag{3.7}$$

$$
\begin{aligned}
\boldsymbol{\mathcal{J}}_e &= \begin{bmatrix} \hat{\mathbf{k}} \times \mathbf{l}_2 & \hat{\mathbf{k}} \times \mathbf{l}_2 \end{bmatrix}_{3\times 2}; \\
\dot{\boldsymbol{\theta}} &= \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix}
\end{aligned}
\tag{3.8}
$$

The matrix $\boldsymbol{\mathcal{J}}_e$ is the Jacobian matrix of the robot which can also map the actuation torque $\boldsymbol{\tau}$,and the external force $\mathbf{F}_{ext}$ acting on the end-effector as:

$$\boldsymbol{\tau} = \boldsymbol{\mathcal{J}}_e{}^T \mathbf{F}_{ext} \tag{3.9}$$

Link Jacobians

In this section, the relationship between the link velocities and the angular speed of the actuators, (i.e., $\dot{\theta}_1$ and $\dot{\theta}_2$) are obtained. The resulting equations are used in formulating the dynamic model. The velocity of the center of mass of the first link can be obtained as:

$$\mathbf{v}_{C,1} = \dot{\theta}_2 \hat{\mathbf{k}} \times \mathbf{r}_1 \tag{3.10}$$

where $\mathbf{r}_1$ is the position of the center of mass of the ith upper arm. Also the angular velocity of the first link can be obtained as:

$$\boldsymbol{\omega}_1 = \dot{\theta}_2 \hat{\mathbf{k}} \tag{3.11}$$

Eq. (3.10) and Eq. (3.11) can be rewritten as:

$$\begin{bmatrix} \mathbf{v}_{C,1} \\ \boldsymbol{\omega}_1 \end{bmatrix}_{6\times 1} = \boldsymbol{\mathcal{J}}_1 \dot{\boldsymbol{\theta}} \tag{3.12}$$

where

$$\boldsymbol{\mathcal{J}}_1 = \begin{bmatrix} \mathbf{0}_{3\times 1} & \hat{\mathbf{k}} \times \mathbf{r}_1 \\ \mathbf{0}_{3\times 1} & \hat{\mathbf{k}} \end{bmatrix}_{6\times 2} \tag{3.13}$$

Similar to link 1, the following relationship could be obtained for the link 2:

$$\begin{bmatrix} \mathbf{v}_{C,2} \\ \boldsymbol{\omega}_2 \end{bmatrix}_{6\times 1} = \boldsymbol{\mathcal{J}}_2 \dot{\boldsymbol{\theta}} \tag{3.14}$$

where

$$\boldsymbol{\mathcal{J}}_2 = \begin{bmatrix} \hat{\mathbf{k}} \times \mathbf{r}_2 & \mathbf{0}_{3\times 1} \\ \hat{\mathbf{k}} & \mathbf{0}_{3\times 1} \end{bmatrix}_{6\times 2} \tag{3.15}$$

The velocity of the center of mass link 3 can be obtained as:

$$\mathbf{v}_{C,3} = \dot{\theta}_2 \hat{\mathbf{k}} \times \mathbf{l}_1 + \dot{\theta}_1 \hat{\mathbf{k}} \times \mathbf{r}_3 \tag{3.16}$$

The angular velocity of link 3 can also be obtained as:

$$\boldsymbol{\omega}_3 = \dot{\theta}_1 \hat{\mathbf{k}} \tag{3.17}$$

Eq. (3.16) and Eq. (3.17) can be rewritten as:

$$\begin{bmatrix} \mathbf{v}_{C,3} \\ \boldsymbol{\omega}_3 \end{bmatrix}_{6\times 1} = \mathcal{J}_3 \dot{\boldsymbol{\theta}} \tag{3.18}$$

where

$$\mathcal{J}_3 = \begin{bmatrix} \hat{\mathbf{k}} \times \mathbf{r}_3 & \hat{\mathbf{k}} \times \mathbf{l}_1 \\ \hat{\mathbf{k}} & \mathbf{0} \end{bmatrix}_{6\times 2} \tag{3.19}$$

Similar to link 3, for the link 4 one could obtain:

$$\begin{bmatrix} \mathbf{v}_{C,4} \\ \boldsymbol{\omega}_4 \end{bmatrix}_{6\times 1} = \mathcal{J}_4 \dot{\boldsymbol{\theta}} \tag{3.20}$$

where

$$\mathcal{J}_4 = \begin{bmatrix} \hat{\mathbf{k}} \times \mathbf{l}_2 & \hat{\mathbf{k}} \times \mathbf{r}_4 \\ \mathbf{0} & \hat{\mathbf{k}} \end{bmatrix}_{6\times 2} \tag{3.21}$$

3.2.3 Acceleration Analysis

In this section, the relationship between the link acceleration and the angular acceleration of the actuators, (i.e., $\ddot{\theta}_1$ and $\ddot{\theta}_2$) are obtained. The resulting equations are used in formulating the dynamic model. By taking the time derivative of Eqs. (3.12), (3.14), (3.18) and (3.20), one could obtain the linear and angular acceleration of the ith-link as:

$$\begin{bmatrix} \mathbf{a}_{C,i} \\ \alpha_i \end{bmatrix}_{6\times 1} = \boldsymbol{\mathcal{J}}_i \ddot{\theta} + \dot{\boldsymbol{\mathcal{J}}}_i \dot{\theta}^2 \tag{3.22}$$

where

$$\dot{\boldsymbol{\mathcal{J}}}_1 = \begin{bmatrix} \mathbf{0}_{3\times 1} & \hat{\mathbf{k}} \times \left(\hat{\mathbf{k}} \times \mathbf{r}_1 \right) \\ \mathbf{0}_{3\times 1} & \mathbf{0}_{3\times 1} \end{bmatrix}_{6\times 2} \tag{3.23}$$

$$\dot{\boldsymbol{\mathcal{J}}}_2 = \begin{bmatrix} \hat{\mathbf{k}} \times \left(\hat{\mathbf{k}} \times \mathbf{r}_2 \right) & \mathbf{0}_{3\times 1} \\ \mathbf{0}_{3\times 1} & \mathbf{0}_{3\times 1} \end{bmatrix}_{6\times 2} \tag{3.24}$$

$$\dot{\boldsymbol{\mathcal{J}}}_3 = \begin{bmatrix} \hat{\mathbf{k}} \times \left(\hat{\mathbf{k}} \times \mathbf{r}_3 \right) & \hat{\mathbf{k}} \times \left(\hat{\mathbf{k}} \times \mathbf{l}_1 \right) \\ \mathbf{0}_{3\times 1} & \mathbf{0}_{3\times 1} \end{bmatrix}_{6\times 2} \tag{3.25}$$

$$\dot{\boldsymbol{\mathcal{J}}}_4 = \begin{bmatrix} \hat{\mathbf{k}} \times \left(\hat{\mathbf{k}} \times \mathbf{l}_2 \right) & \hat{\mathbf{k}} \times \left(\hat{\mathbf{k}} \times \mathbf{r}_4 \right) \\ \mathbf{0}_{3\times 1} & \mathbf{0}_{3\times 1} \end{bmatrix}_{6\times 2} \tag{3.26}$$

3.3 Dynamic Analysis

Several methods have been proposed for deriving the dynamic model of multibody systems including the Newton-Euler formulation [31,122], the Lagrangian formulation [88,94], and the principle of virtual work [4,133]. The robot in this research is a parallel mechanism[1] and for parallel manipulators, the principal of virtual work has been stated to be one of

---

[1] Parallel mechanism is referred to a mechanism that have one or more paths from ground to end-effector [85].

the most efficient approaches for the dynamic analysis [133]. Hence, in this paper, the principle of virtual work is used for deriving the inverse dynamics of the manipulandum.

For the inverse dynamics problem, it is assumed that a desired path of the end-effector is assigned and the problem is to determine the required input forces/torques to produce that desired motion. To simplify the model in this research, the frictional forces and torques are neglected, and the only change in virtual work is correlated with the applied inertia forces/torques. If desired, friction can be included in a more complex robot model, as in [42]. The inertia forces and torques for ith- link can be obtained as:

$$\boldsymbol{\mathcal{F}}_i = -\begin{bmatrix} m_i \mathbf{a}_{C,i} \\ I_{C,i} \boldsymbol{\alpha}_i \end{bmatrix} \tag{3.27}$$

The principal of virtual work can be stated as:

$$\delta\boldsymbol{\theta}^T \boldsymbol{\tau} + \delta\mathbf{r}_e{}^T \mathbf{F}_{Ext} + \sum_{i=1}^{4} \delta\boldsymbol{\mathcal{X}}_i{}^T \boldsymbol{\mathcal{F}}_i = 0 \tag{3.28}$$

where $\boldsymbol{\tau} = [\tau_1 \quad \tau_2]^T$ represents the actuated torques and $\delta\theta = [\delta\theta_1 \quad \delta\theta_2]^T$ is the column matrix of virtual displacements of the actuators. In addition, $\boldsymbol{\mathcal{X}}_i$ denotes the virtual displacements of the ith-link. By using Eqs. (3.12), (3.14), (3.18), (3.20) and (3.7) $\delta\mathbf{r}_e$ and $\delta\boldsymbol{\mathcal{X}}_i$ can be obtain as:

$$\delta\mathbf{r}_e = \boldsymbol{\mathcal{J}}_e \delta\boldsymbol{\theta} \tag{3.29}$$

$$\delta\boldsymbol{\mathcal{X}}_i = \boldsymbol{\mathcal{J}}_i \delta\boldsymbol{\theta} \tag{3.30}$$

Substituting Eqs. (3.29) and (3.30) into Eq. (3.28) yields:

$$\delta\theta^T(\tau + \boldsymbol{\mathcal{J}}_e{}^T\mathbf{F}_{Ext} + \sum_{i=1}^{4}\boldsymbol{\mathcal{J}}_i{}^T\boldsymbol{\mathcal{F}}_i) = 0 \tag{3.31}$$

Since the latter equation is valid for any arbitrary $\delta\theta$, it follows that:

$$\tau + \boldsymbol{\mathcal{J}}_e{}^T\mathbf{F}_{Ext} + \sum_{i=1}^{4}\boldsymbol{\mathcal{J}}_i{}^T\boldsymbol{\mathcal{F}}_i = \mathbf{0} \tag{3.32}$$

Equation (3.32) can be rewritten in a standard form as:

$$\boldsymbol{\mathcal{M}}(\theta)\,\ddot{\theta} + \boldsymbol{\mathcal{C}}(\theta,\dot{\theta}) = \tau + \boldsymbol{\mathcal{J}}_e{}^T\mathbf{F}_{Ext} \tag{3.33}$$

Where $\boldsymbol{\mathcal{M}}(\theta)$ is a mass matrix, which is symmetric positive-definite and $\boldsymbol{\mathcal{C}}(\theta,\dot{\theta})$ is the column matrix of centrifugal and Coriolis terms.

$$\begin{aligned}
\boldsymbol{\mathcal{M}}(\theta) &= \sum_{i=1}^{4}\boldsymbol{\mathcal{J}}_i{}^T\begin{bmatrix} m_i\mathbf{1}_{3\times3} & \mathbf{0} \\ \mathbf{0} & I_{C,i}\mathbf{1}_{3\times3}\end{bmatrix}\boldsymbol{\mathcal{J}}_i \\
\boldsymbol{\mathcal{C}}(\theta,\dot{\theta}) &= \left(\sum_{i=1}^{4}\boldsymbol{\mathcal{J}}_i{}^T\begin{bmatrix} m_i\mathbf{1}_{3\times3} & \mathbf{0} \\ \mathbf{0} & I_{C,i}\mathbf{1}_{3\times3}\end{bmatrix}\dot{\boldsymbol{\mathcal{J}}}_i\right)\dot{\theta}^2
\end{aligned} \tag{3.34}$$

3.4 Model verification using MapleSim

The author conducted a simulation study to verify the obtained model. In order to do so, for a desired trajectory, the actuator torques obtained from the proposed analytical model,

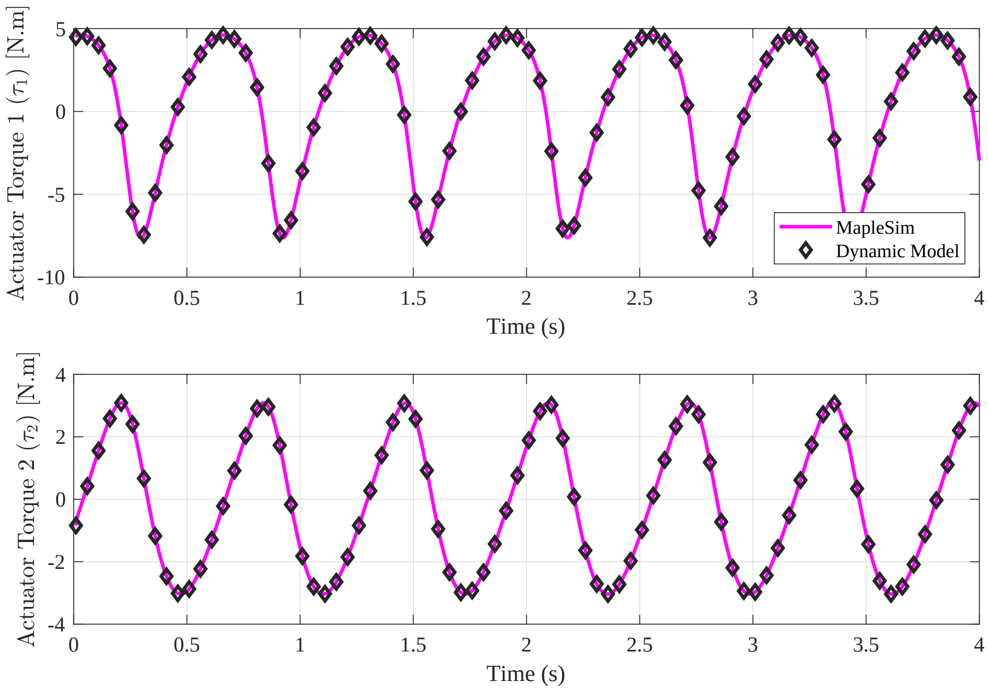


Figure 3.3: Comparison between the actuator torques obtained from the obtained dynamic model and those given by the adapted MapleSim model.

(i.e., Eq. (3.33)) are compared with those obtained from the adapted MapleSim model from [42]. The computed and measured torques for the trajectory stated below are shown in Fig. 3.3.

$$\begin{aligned} x(t) &= -0.2 + 0.1\sin(10t) \\ y(t) &= 0.3 + 0.1\cos(10t) \end{aligned} \tag{3.35}$$

The maximum error was less than 9.8×10^{-3} N.m for the simulation performed, which indicates the accuracy of the model. The parameters used for the analytical model, are shown in Table 3.1.

Table 3.1: The inertia parameters of the manipulandom [42]

Parameter	Unit	Value
l_1	m	0.100
l_2	m	0.310
l_3	m	0.310
l_4	m	0.375
m_1	kg	2.5783
m_2	kg	3.3986
m_3	kg	0.0620
m_4	kg	1.0832
I_1	$kg.m^2$	0.0224
I_2	$kg.m^2$	0.0606
I_3	$kg.m^2$	0.0007
I_4	$kg.m^2$	0.0098
r_1	m	0.0051
r_2	m	0.0012
r_3	m	0.1576
r_4	m	0.2745

3.5 Conclusion

In this chapter, first, an overview of the robot system is given, focusing on its mechanical design and computer software. Then, the kinematic and dynamic models of the robot are presented. The dynamic model was obtained from the principal of virtual work and has been verified using MapleSim software. The results have shown that the obtained dynamic model is valid and will be further used in control implantation in chapter 4. The followings are the contribution of the author in this chapter:

1. Deriving the dynamic model of the manipulandum rehab robot using the principal of virtual work method.

2. Verifying the dynamic model with the MapleSim software.

Chapter 4

Robot Control

Among several challenges that are associated with the design of rehabilitation robots (e.g., the design of the mechanical structure, the actuator type, and the control strategies), the control strategies is the most critical to create a more efficient rehabilitation robot [6,131]. The focus of this chapter will be on describing the controller developed through this thesis research.

4.1 Motion Control

As mentioned in Section 3.1, rehabilitation robots provide two main modes of therapy, (i.e., passive and active) [6, 109]. Motion control (trajectory tracking) is usually designed for the passive mode of training, which often aims to accurately follow the desired trajectory within the workspace of the robot [6,62] without considering the effort of the patient. In this controller, the torques required for the desired trajectory have to be computed and applied to the robot's actuators. These required torques are the control output of the motion controller. In many cases, feedback from the joint sensors can be used to compute the required torques . [25, 108, 121].

In order to calculate the required torque for a particular motion, one possible solution is to use the dynamic equation as obtained in Eq. (3.33). Ideally, if the dynamic model were completely accurate, the data obtained from the force sensor to measure the user's hand force were precise, and no disturbances were present, one could apply the obtained torques from the model to follow the trajectory. However, computed torque control strategy could be impractical for the real application due to the presence of an imperfection in the dynamic model and the unavoidable disturbances [25]. This control strategy is called open-loop control system, since the feedback from the sensors is not used and the controller is a function of only the desired trajectory ($\boldsymbol{\theta}_\mathbf{d}$), and its derivatives ($\dot{\boldsymbol{\theta}}_\mathbf{d}$ and $\ddot{\boldsymbol{\theta}}_\mathbf{d}$).

Generally, in order to create a high-performance control system, one may require to use the sensor feedback [25]. Such control strategy that makes use of the feedback is called a closed-loop control system. This feedback is often used to compute the tracking error which could be obtained by calculating the difference between the desired and the actual joint angles and the difference between the desired and the actual joint speeds:

$$\mathbf{e} = \boldsymbol{\theta}_\mathbf{d} - \boldsymbol{\theta} \tag{4.1}$$

$$\dot{\mathbf{e}} = \dot{\boldsymbol{\theta}}_\mathbf{d} - \dot{\boldsymbol{\theta}} \tag{4.2}$$

4.1.1 Feedback Control

PID (Proportional - Integrative - Derivative) controllers are one of the common forms of feedback control. PIDs were introduced in 1940 and have been extensively used in industrial applications [1, 8]. The success of PID controllers is because of their simple structure, robustness, and easiness of tuning their parameters. In this study, since the steady-state error was not observed in simulation and experimental studies, the integral term of the controller is not needed, and a PD controller was chosen instead of the PID controller. The block diagram of the PD controller that is used in this research is shown in Fig. 4.1

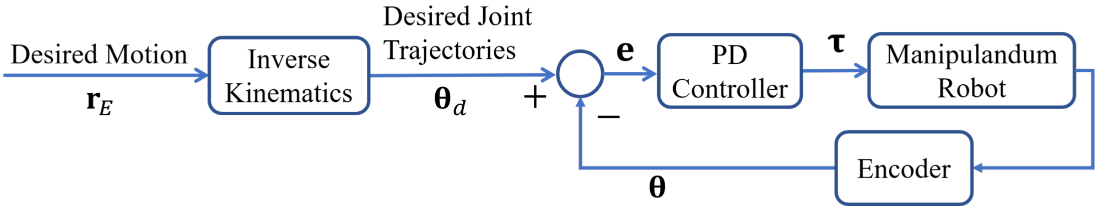


Figure 4.1: Block diagram of PD controller

In the diagram shown in Fig. 4.1, the inverse kinematics obtained in chapter 3 is used to find the desired value of joint trajectories ($\boldsymbol{\theta}_\mathbf{d}$) from the desired motion or trajectory of the end-effector ($\mathbf{r_E}$). The measured actual joint angle values ($\boldsymbol{\theta}$) of the robot from motor encoders are compared to its desired value to obtain the error vector ($\mathbf{e}$). The PD controller uses this error information to generate suitable commands for the actuators to minimize the tracking error. The controller is designed based on the joint space error obtained from Eq. (4.1) and is implemented in the joint space. The output of the controller is the actuator torque ($\boldsymbol{\tau}$), which is also represented in the joint space. The controller command consists of:

$$\boldsymbol{\tau} = K_p \, \mathbf{e} + K_d \frac{d}{dt}\mathbf{e} \tag{4.3}$$

where K_p is the proportional gain and K_d is the derivative gain.

The design of the PD controller usually does not require dynamic analysis and is relatively easy to implement [116]. Choosing the proper gain for the PD controller is necessary to keep the performance of the system. Manual tuning, trial, and error, Ziegler-Nichols method, or model-based methods [62] are some of the common approaches for tuning the controller gains. Usually, the final controller gains are calculated as a trade-off between steady-state errors and transient response. Because of the nonlinear nature of robotic systems, the gains are usually tuned for a home configuration of the robot. So depending on the distance from the home configuration, the performance of the designed controller could vary. This makes the tuning process a difficult task [116]. Marcia et al. [92] controlled a RiceWrist to have a motion control using the traditional fixed gain PD controller and found that the performance of this controller is dependent on the selection of its proper PD gains and for different configurations, the performance could vary substantially.

4.1.2 Feed Forward - Feedback controller

One method to circumvent the problems of PD controllers which are the result of the nonlinear behavior of robotic systems is including the dynamic model of the system inside the control loop. Using the inverse dynamic model could eliminate the challenge due to non-linearity by providing estimated required torques as shown in Fig. 4.2.

In this method, due to the presence of the dynamic model, the error will be configuration

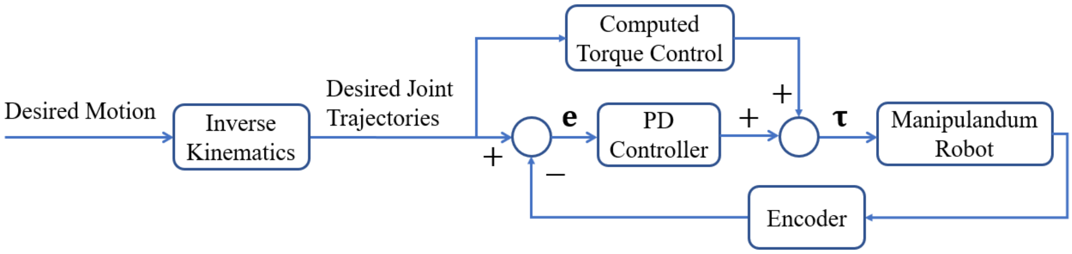


Figure 4.2: Block diagram of feed forward - feedback controller

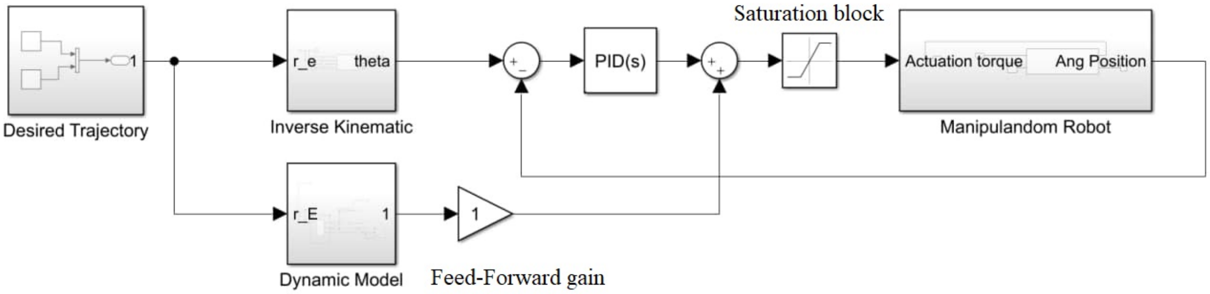


Figure 4.3: The block diagram of the simulation study in Simulink.

independent and therefore, it is easier to tune the PD controller gains to work well within the whole workspace of the robot [116].

4.1.3 Simulation Studies

The main blocks of the simulation are depicted in Fig. 4.3. A PD controller with $K_p = 2$ and $K_d = 0.2$ was used in the simulations. The gains were obtained by using the PID tuner toolbox of Matlab. To make the simulations more realistic, a saturate block was used to limit the actuation torques. Based on the mechanical transformer's gear ratio and the maximum continuous torque of the motors reported in [42], the maximum output torque was calculated to be 2.2 N.m. A feed-forward gain is used to switch between the feed-forward-feedback approach (with gain equal to 1) and pure feedback controller (with gain equal to 0). The simulation results are shown in Fig. 4.4. The trajectory was a circular path and the controllers aimed to precisely follow the desired path. The errors in the X and Y direction are shown in Fig. 4.5.

4.1.4 Results and Discussion

As can be seen in Fig. 4.5, the error in both X-direction and Y-direction is better in Feed-Forward-feedback controller compared to the pure feedback controller.

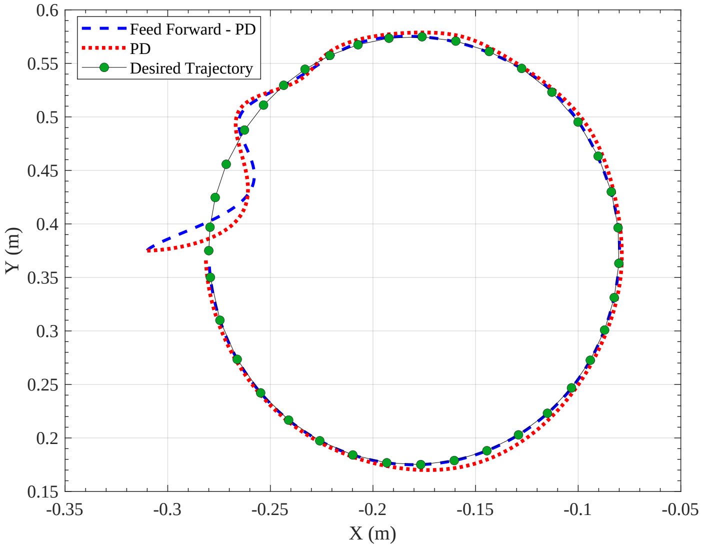


Figure 4.4: Trajectory tracking comparison between feedback and feed forward-feedback controller

Motion control is appropriate when the purpose of the therapy is just tracking a specified trajectory where patients are weak and passive training is needed [109]. For example,

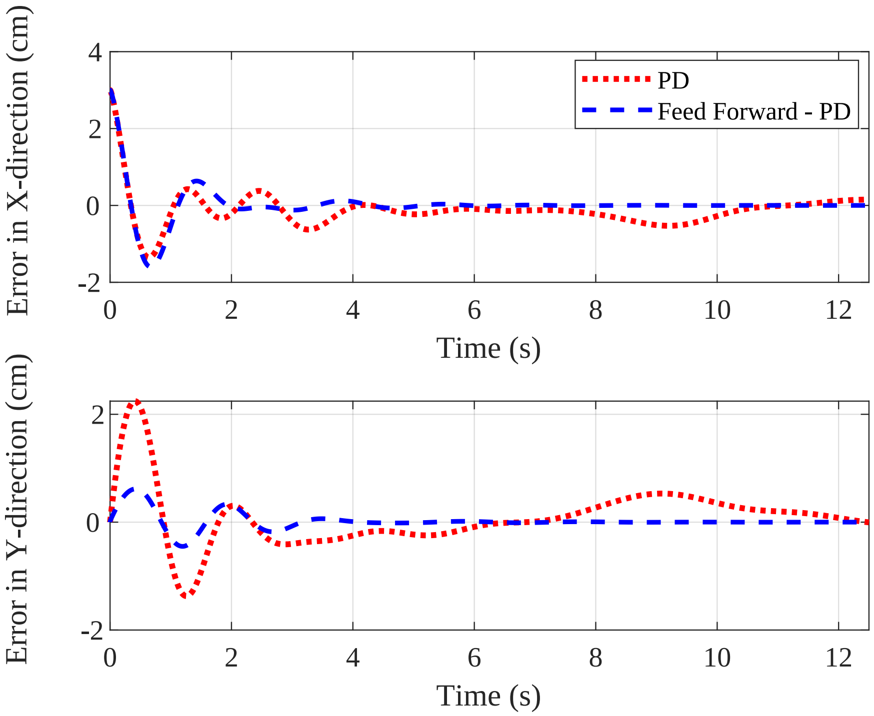


Figure 4.5: The trajectory error of the proposed controllers

patients with more severe impairments are more likely to benefit from motion control since the real need is to enhance the range of motion rather than function. Motion control is also relatively simple to implement in the robot.

However, motion control is time-dependent, meaning that the robot will force the patient's hand to be in a certain location. In some cases, where the interaction of the patient is required, this may not be appropriate since it does not provide timing freedom for patients to perform the reaching task. Patients with mild or moderate impairment often need to be engaged in exercise [6,22] and not to be forced to be in a specific position at a specific time.

In addition, motion control is path independent, meaning that if the patient does not complete the reaching task in a given time, the robot forces the patient to reach the desired target without considering the specified desired trajectory.

4.2 Force-Field Control

The force field control method is one of the approaches that could solve the problems associated with motion control discussed in the previous section. Unlike motion control, this method provides the timing freedom to perform a reaching task [10, 11, 111].

Adaptation using force field and its after-effect has been studied for different types of force-fields, including position, velocity, and acceleration-dependent force fields [17, 24, 36, 40, 106], curl fields that produce perpendicular forces to the velocity of the hand [40], and Coriolis forces which result from moving in a rotating room [69]. Studies involving force fields are usually conducted using a robot arm (robotic manipulandum) [106].

Force-field adaptation could be a possible method for rehabilitation that may lead to beneficial after effects. This may be true if stroke patients can adapt to the new environment with the presence of disturbance force fields. Patton et. al. [96] tested the force-field method on 18 stroke patients. The method was to push the patients' hands proportionally to its speed and perpendicularly to its motion direction. They found that the resistive mode of therapy could be more effective compared to the assistive mode.

Most of controllers that are implemented using force-field methods usually cannot be tuned to suit a specific patient due to their fixed set of control parameters [9, 74, 113].

Subject specific controller can help to achieve a desirable performance for each patient [113]. In this research, a novel force-field control algorithm is proposed for a manipulandum robot available in the Motion Research Group at the University of Waterloo (Fig. 3.1) which is followed by proposing a subject-specific algorithm that can adjust the control parameters based on each given patient.

4.2.1 Methodology

As each stroke patient is affected differently, each requires treatment that is best tailored for him/her, therefore the robot should be able to adjust the path and intensity of exercises according to the patient.

In the literature, two different types of stroke patients are identified during a reaching task [64]:

1. Patients who make fast movements but aim poorly.
2. Patients who aim well but move very slowly.

The patients categorized in the first group have the power to move their hand, but the coordination of the muscles are poor which may represent itself in high lateral error in point to point reaching tasks. On the other hand, the second type of patient has good muscle coordination, but the muscle force is not enough to perform the task in a given time. In order to address each type of patient, two main novel force fields were proposed in this research as follows:

1) Force field along the desired trajectory (Channel field): As shown in Fig. 4.6, depending on the type of exercise, this field helps or challenges the patient to stay on the desired trajectory. The patients in the first category may benefit from this field. This field was modeled as:

$$\mathbf{F}_c = M_c \tanh\left(K_c \left\| Rej(\mathbf{r}_{sg})\left(\mathbf{r} - \mathbf{r}_s\right)\right\| / M_c\right) \hat{\mathbf{e}}_c \tag{4.4}$$

where $\mathbf{r}_{sg}$ denotes the vector connecting the starting point to the goal point, M_c is the maximum value of the magnitude of this field, K_c is the stiffness of the field, $\mathbf{r}$ is the current position of the hand, $\mathbf{r}_s$ is the position of the starting point and $Rej(\mathbf{r}_{sg})$ is called the rejection matrix for $\mathbf{r}_{sg}$ which is obtained as:

$$Rej(\mathbf{r}_{sg}) = \frac{\mathbf{r}_{sg}{\mathbf{r}_{sg}}^T}{{\mathbf{r}_{sg}}^T\mathbf{r}_{sg}} - \mathbf{1}_{2\times 2} \tag{4.5}$$

The vector rejection of vector **a** on **b** is illustrated in Fig. 4.7. Also, $\hat{\mathbf{e}}_c$ is the unit vector along the rejection vector which is obtained as:

$$\hat{\mathbf{e}}_c = \frac{Rej(\mathbf{r}_{sg})\left(\mathbf{r} - \mathbf{r}_s\right)}{\left\| Rej(\mathbf{r}_{sg})\left(\mathbf{r} - \mathbf{r}_s\right)\right\|} \tag{4.6}$$

The hyperbolic tangent (tanh) has been used to impose a saturation to the magnitude of the force.

2) Force field toward the target (Radial field): This field, as depicted in Fig. 4.6, will apply force towards the target. In the assistive mode, by adding this field, a helping force will guide the patient towards the target. In case of resistive mode, this field will make the

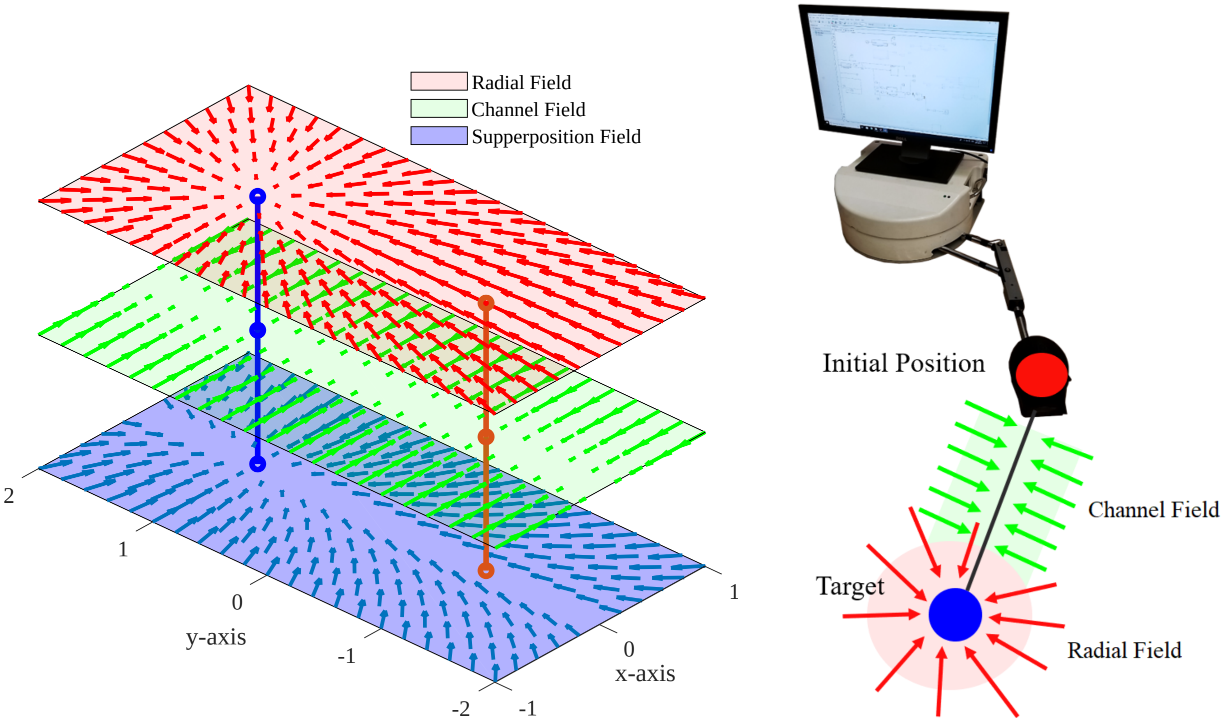


Figure 4.6: An illustration of the defined force fields. Red field denotes the radial force field toward the target and the green field represents the channel trajectory field. The blue field is the superposition of the two fields.

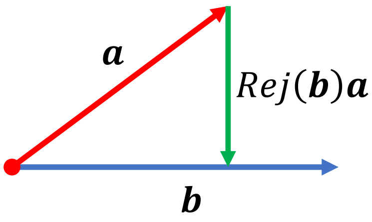


Figure 4.7: The vector rejection of vector **a** on **b**.

reaching task more challenging. This field may help the patients categorized in the second group. This field was modeled as:

$$\mathbf{F}_r = M_r \tanh\left(K_r \left\|\mathbf{r}_g - \mathbf{r}\right\| / M_r\right) \hat{\mathbf{e}}_r \tag{4.7}$$

where M_r is the upper limit of the magnitude of the force and K_r is the stiffness of the force relative to the displacement, $\mathbf{r}_g$ denotes the position of goal point, and,

$$\hat{\mathbf{e}}_r = \frac{\mathbf{r}_g - \mathbf{r}}{\|\mathbf{r}_g - \mathbf{r}\|} \tag{4.8}$$

In addition to the aforementioned force fields, a damping force was considered to help with system stability, which can be obtained as:

$$\mathbf{F}_{damp} = -C\dot{\mathbf{r}} \tag{4.9}$$

where C is the damping coefficient.

4.2.2 Subject-Specific Adaptation

Ideally, a rehabilitation robot should be able to adjust the provided assistance in therapy sessions based on the subject's performance and ability [137]. In this section, an adaptive algorithm was proposed to automatically adjust the introduced force fields.

The stiffness of the force fields were selected as the variables for adaptation. By changing the stiffness of the fields, the strength of fields can be adjusted. Greater value of stiffness results in more assistance or resistance. For example, patients who have great lateral error should get more assistance in the lateral direction so the adaptation rule should increase the stiffness of the channel field, (i.e., K_c), for these patients. Similarly, patients who have difficulty in reaching to the goal should get more assistance towards the goal position which is possible by increasing the stiffness of the radial field, (i.e., K_r). The following mathematical formula was proposed as the adaptation rule to encapsulating the aforementioned requirements:

$$K_c\left(t\right) = K_{c,0} + C_c \int\limits_{\tau=0}^{t} \lambda^{\tau-t} {e_c}^2(\tau) d\tau \tag{4.10}$$

$$K_r\left(t\right) = K_{r,0} + C_r \int\limits_{\tau=0}^{t} \lambda^{\tau-t} {e_r}^2(\tau) d\tau \tag{4.11}$$

where $K_{c,0}$ and $K_{r,0}$ are the initial stiffness values and C_c and C_r are constant gains for regulating the sensitivity of the change of stiffness values to the errors. Furthermore, a forgetting factor, (i.e., $0 < \lambda < 1$), was used to give less weight to older error values and make the adaptation more sensitive to the recent outcomes. Channel error e_c and radial error e_r have been depicted in Fig. 4.8.

4.2.3 Simulation Studies

This section presents a simulation study that was performed to evaluate the effectiveness of the proposed force field-based method.

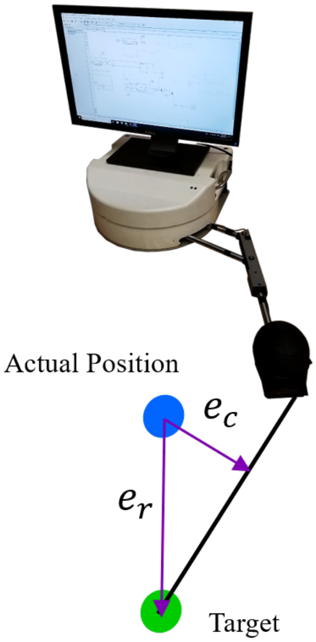


Figure 4.8: Representation of channel and radial error

Model of the patient:

In this research, due to COVID-19, access to real patients was not possible. Hence, to evaluate the algorithms, a mathematical model of motor control of post-stroke patients was derived. Shadmehr et. al [106] proposed a human motor control model for healthy subjects. In this model, it is assumed that the subject has proportional-derivative feedback which can be obtained as:

$$\mathbf{u}_{fb}\left(t\right) = P\mathbf{e}_g + D\dot{\mathbf{e}}_g \tag{4.12}$$

where P and D are the proportional and derivative gains, and $\mathbf{e}_g(t) = \mathbf{r}_g(t) - \mathbf{r}(t)$ is the difference between the desired and current hand position at time t. Furthermore, they realized the feedback controller does not fully match with the motor control of humans due to the inherent delay in feedback signal to the brain. So they added a feed-forward term to the model. This feed-forward command is modeled as:

$$\mathbf{u}_{ff}{}^{n}(t) = \alpha \mathbf{u}_{fb}{}^{n-1}(t) + (1-\gamma)\,\mathbf{u}_{ff}{}^{n-1}(t) \tag{4.13}$$

where α and γ are respectively, constant weights determining the contributions of previous feedback and feed-forward commands on the current feed-forward command.

In this research, based on the movement disorders after stroke reported in [12], which mostly involve involuntary sustained contraction or twitching of muscles, a constant disturbance command was added to the motor command denoted by $\mathbf{u}_{stroke}$. Hence the total control command for post-stroke patients in this research was modeled as:

$$\mathbf{u}(t)^{n} = \mathbf{u}_{fb}(t)^{n} + \mathbf{u}_{ff}(t)^{n} + \mathbf{u}_{stroke} \tag{4.14}$$

where $\mathbf{u}$ is the force of the hand applied to the end-effector.

The simulations were executed in MATLAB Simulink. A general schematic of the block diagram of the simulation is provided in Fig. 4.9. In addition, a screenshot of the simulation environment is depicted in Fig. 4.10. Referring back to Fig. 4.9 there are two inputs to the robot: the first input is the designed force-field which is mapped to the actuation torques $\boldsymbol{\tau}$ by using the Jacobian matrix obtained in Section 3.2.2. The second

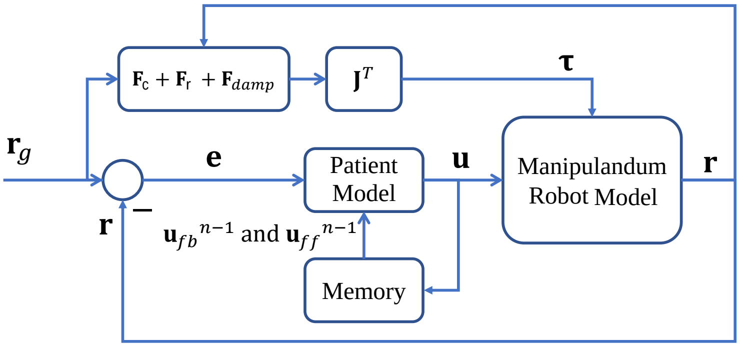


Figure 4.9: A schematic of the block-diagram of the simulation.

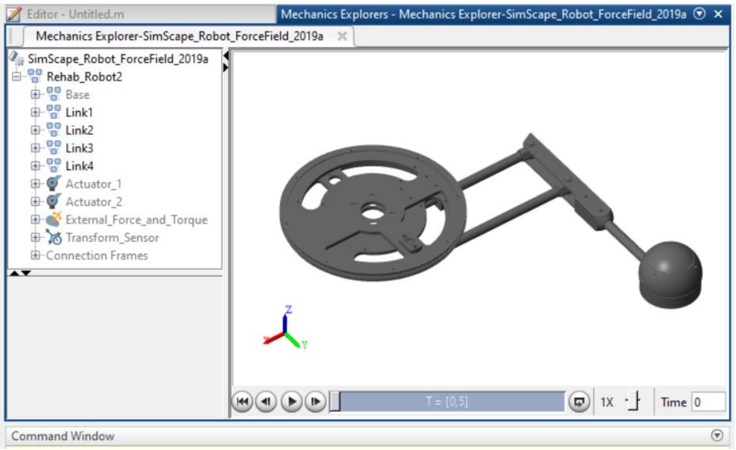


Figure 4.10: The SimScape model of the Manipulandom robot.

input is the external force on the end-effector from the patient, (i.e., $\mathbf{u}$). The objective of the simulation result was to compare the effectiveness of the force fields in the assistive and resistive mode of therapy. In the simulation, the task was to complete a reaching movement from a starting point to an endpoint. The simulated therapy sessions consisted of three phases:

1. First, the patient did 2 trials without involving the robot (Null field).

2. Then, 6 trials were done by adding the proposed force fields using the robot.

3. Finally, similar to the first phase, 2 trials were done without robot intervention (Null field). By comparing the performance of the subject in this phase and the initial phase, the effectiveness of the therapy can be evaluated. The patient model has been trained in the exercise and as can be concluded, the result of this phase is different than the first phase of training.

4.2.4 Results

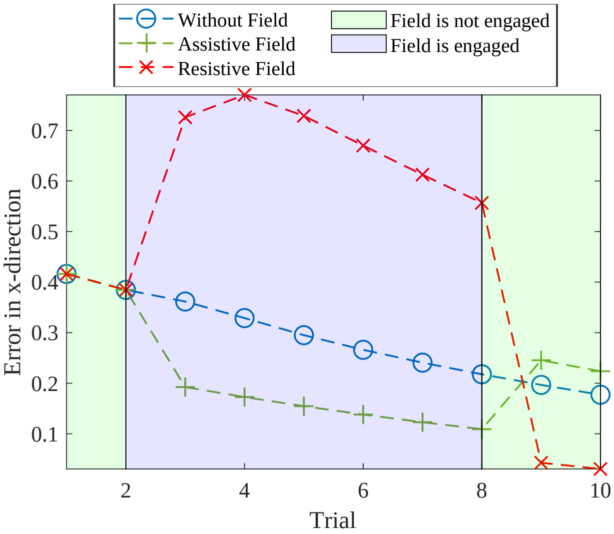


Figure 4.11: Error in x-direction vs trials number for different fields.

For all of the simulations, the starting point is $\mathbf{r}_s = [-0.31 \quad 0.375]$ (m) and the target point is $\mathbf{r}_g = [0.4 \quad 0.375]$ (m). The results of the simulations are shown in Fig. 4.11, Fig. 4.12 and Fig. 4.13. By looking into Fig. 4.11 and Fig. 4.12, one can observe that the patient has the best performance during therapy in assistive mode but after therapy the same subject will have the worst performance compared to two other therapy modes, (i.e,

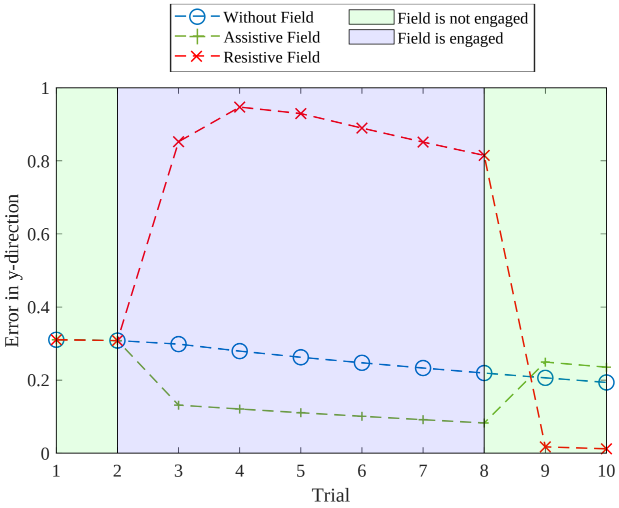


Figure 4.12: Error in y-direction vs trials number for different fields.

null field and resistive field). On the other hand, for the resistive mode the patient has the worst performance during the therapy, while the performance after the therapy is better compared to the other two.

The same conclusion could be made by inspecting Fig. 4.13, which depicts the trajectory of the hand during different trials. This phenomenon could be explained by considering the feed-forward command of the patient; as it is apparent from Fig. 4.13, more resistance during therapy will result in more position error and consequently, more feedback gain and eventually greater value of feed-forward gain. The high value of feed-forward gain will help the patient to reach the target easier after the resistance field is removed. Better performance after resistance mode of training has also been observed experimentally in a study by Patton et al., [96], which indicates that resistive modes of training have more impact on the motor function recovery of the stroke patients [38, 96].

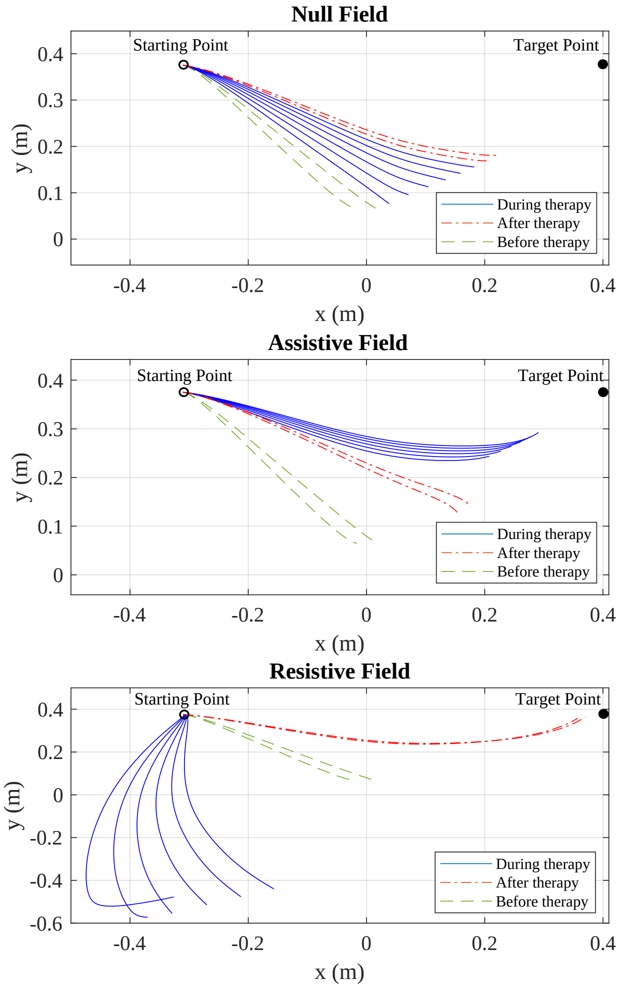


Figure 4.13: Effect of different types of fields on the performance of the simulated patient. The green dashed line indicates the estimated performance of the patient before therapy. Solid blue lines represent the simulated hand trajectory during therapy and the dotted red lines are the final performance after the therapy.

4.3 Discussion

In this chapter, two methodologies, namely, motion and force-field control, were proposed and investigated to control the manipulandum robot for rehabilitation purposes. The mo-

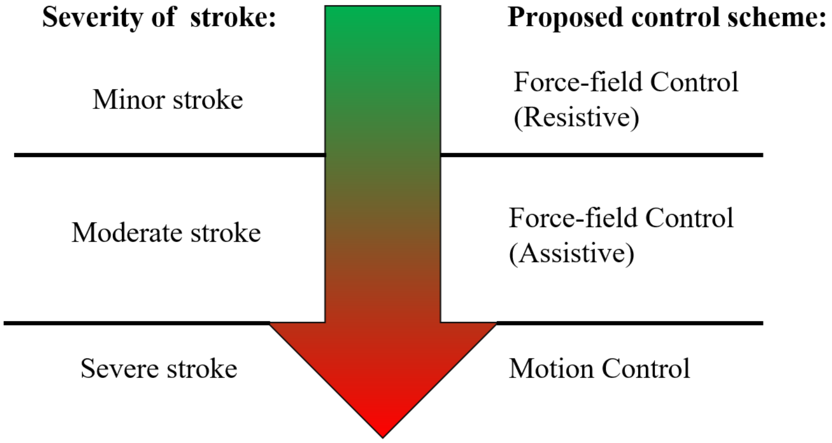


Figure 4.14: The proposed control scheme based on the severity of the stroke. The category of severity of the stoke is taken from [45]

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tion control algorithm can precisely follow a prescribed time-dependent trajectory whereas the force-control method will only provide assistance (or even resistance to introduce extra challenge) to the patient to do the task rather than forcing the movement. Each method could have benefits depending on the type of patient and the severity of the impairment of motor control due to stroke. For example, as mentioned above, patients with more severe impairments are more likely to benefit from motion control since the real need is to enhance the range of motion rather than function, therefore motion control is likely of more benefit for those types of patients. For less severe patients with a decent-to-good range of motion, the goal is to promote motor function (or skill motor learning); in this latter case, a force-field may be more beneficial for promoting motor functionality. Fig. 4.14, depicts the possible usage of each algorithm depending on the patient type.

In addition, a novel adaptive algorithm was proposed for fine-tuning the proposed force-field parameters based on the performance of the patient during the therapy. The effectiveness of the adaptation rule will be evaluated on real patients in the future. By considering that during the time that this research was conducted, access to a real stroke patient was not possible due to COVID-19, a simulation study was established to perform a preliminary evaluation of the performance of the algorithms. To do so, first, a motor control model of post-stroke patients was proposed. Then, by making the virtual patient go through a therapy session, the algorithms are evaluated by comparing the performance of the patient before and after the therapy. It was observed that the force-field algorithm has a positive effect on the motor control recovery of the virtual patient. Furthermore, the simulation results also indicated that the resistive mode of therapy would result in better outcomes after the therapy which agrees with observations in experimental studies by other researchers [38, 96].

The results were limited by the accuracy of the patient model and as future work, the effectiveness of the proposed algorithm has to be further investigated in both resistive and assistive mode by implementing the algorithm on the robot and testing it on real subjects. It should be noted that the conclusions made here are based on the assumption that the patient model provided in Section 4.2.3 is close to the behavior of a real stroke patient. For future studies, it is a hope to test these different modes of therapy on real stroke patients.

While this study proposed that a given patient may benefit from exposure to the force fields, it is worthy to mention that straightness of the hand trajectory may not be a key goal of therapy, this has been stated by Patton et. al [96] and the feedback from the therapists who participated in different stages of this thesis. In addition, stroke patients may have a slower rate of learning compared to the healthy subject, which might affect the patient model. Also, the psychological effects of the therapies on the patient may affect the performance of the patient, which is not studied in this research.

4.4 Conclusion

In this chapter, two control strategies, namely, motion and force-field control, was proposed and implemented to control the manipulandum rehabilitation robot showed in Fig. 3.1. In addition, a novel subject specific adaptive algorithm was proposed for fine-tuning the force-field control parameters.

The followings are the contribution of the author in this chapter:

1. Designing and implementing a motion controller for an upper limb rehabilitation robot using feedback and feed forward-feedback controller.
2. Designing and implementing novel force-field controllers (e.g., radial and channel fields) in two main modes of rehabilitation training, (i.e., assistive and resistive).
3. Proposing a stroke patient model and evaluating the performance of the model in simulation studies.
4. Proposing a novel adaptive force-field for fine tuning the proposed force-field control parameters.

Chapter 5

Collaborative Design of a Graphical User Interface

5.1 Overview

In order to interact with robot-assisted therapy, therapists need to have access to a User Interface (UI). The UI is how human users interact with hardware (e.g., a computer or a robot) and software (e.g., a website or application); touch screens, and keyboards are examples of UI. A Graphical User Interface (GUI) is a user interface that enables people to have interaction with electronic devices through graphical icons [100]. An appropriate GUI that enables therapists to control the robot is a key element of the potential usability of robot-assisted therapy in rehabilitation. A good GUI could facilitate user-robot interaction during the treatment session [60], including what, how, and when feedback is provided.

Most of the research related to robot-assisted therapy has not investigated the design of the GUI and GUI development and user involvement in its design often does not appear to occur in the research [59]. Huq et al. [53] developed a portable upper limb robotic system similar to the robot used in this research and they evaluated their system along with its GUI with seven therapists in a focus group study. They found that the GUI needs improvement by adding assistance and resistance force levels to represent more real-world force levels that are realizable by the therapists and patients. They further found that the GUI needs improvement to meet the patient's visual impairments and to provide a useful format for the performance evaluation data for further analysis [53]. The purpose of this second portion of the thesis is to work with therapists to design an intuitive GUI for therapists to enable them to control a robot for supporting post-stroke upper-limb rehabilitation and to enable them to provide objective information on patients' performance. By involving therapists in the design of the GUI and by reflecting on their needs and preferences, it is anticipated that the resulting GUI for controlling the robot will be more intuitive for them to do [100].

The GUI design research was executed in six stages as follows and are described in the following subsections in greater detail:

1. Constructing the initial GUI interface mock-up using MATLAB app designer and PowerPoint.
2. Evaluating the initial version of the mock-up by eliciting therapists' opinions regarding the features and elements of the GUI through semi-structured interviews [1].

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[1] Semi-structured interviews are balanced between questions with standardized format and fixed and open-ended response options. [105]

3. Analyzing the qualitative data using an affinity diagram [2] to capture the therapist's feedback and needs.

4. Revising the GUI based on therapists' feedback.

5. Conducting a second interview to show the revised version of the GUI to therapists and receive their another round of feedback.

6. Summarizing the key findings and recommendations in main topics and expose the disagreement among participants.

5.2 Initial GUI Design

The initial GUI was designed based on reviewed literature, research team expertise, and a consultation with an occupational therapist academic who previously designed a GUI for the similar model of robot used in this research (but with a different controller and end effector) [21,52,53,56,57,59,75,135]. The GUI has two main tabs (screens), the exercise adjustment tab (Fig. 5.1) and the performance evaluation tab (Fig. 5.3).

1. **The exercise adjustment tab** consists of:

    (a) The *robot and patient work-space:* This panel is located on top left on Fig. 5.1 where therapists and patients are able to see the work-spaces of the robot

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[2] The affinity diagram is a popular and powerful method for performing qualitative data analysis and organization [49,61,93].

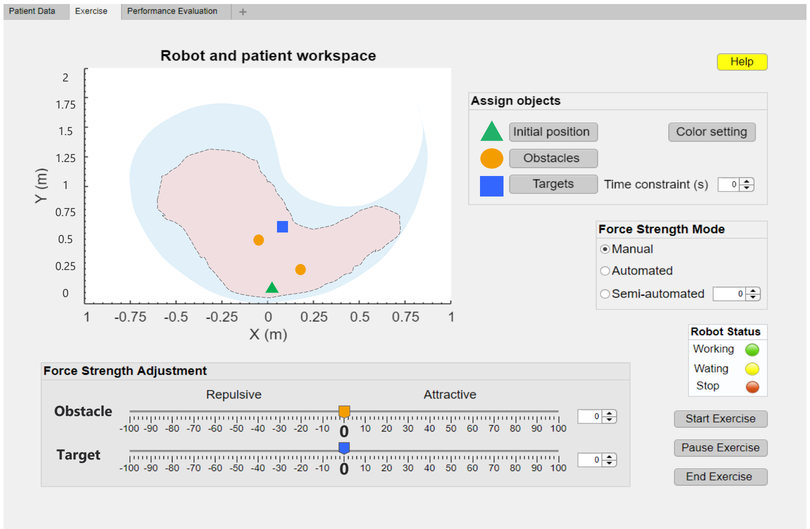


Figure 5.1: Exercise adjustment section of initial GUI design

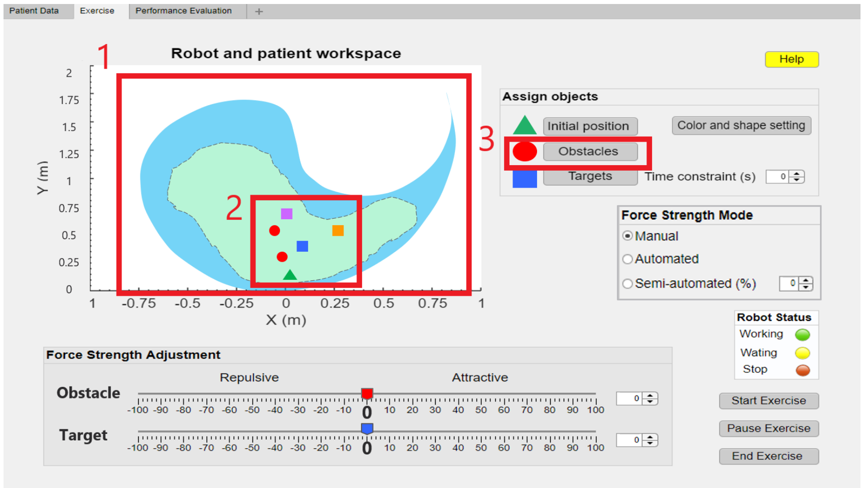


Figure 5.2: Exercise adjustment section of the revised GUI design. The red boxes and numbers indicate the changes that have been made to the revised GUI.

and the patient (i.e., where each can reach in the different regions of the work-space) during the rehabilitation session. The patient work-space represents the patients' maximum reach space and will be updated based on each patient. The idea of having a robot and patients work-space was inspired from the previous study by Huq et al. [53]. They used the patient and robot work-space for visual feedback where patients and therapists can see the maximum space that the robot can cover and the maximum space that patients can reach within the robot work-space.

(b) The *assign objects panel:* This panel allows the location of the starting position, targets, and obstacles to be defined by the therapist. The procedure of assigning objects is as follows: first, therapists select the initial position where the patient should start the exercise, obstacles where the patient should avoid the different regions of the work-space like internal rotation, and finally the targets where the patient should reach to. The idea of having an initial position and a target position for a rehabilitation exercise was inspired from the previous studies by Hung et al., and Keller et al., [52, 57], the obstacles have been added to this section as a new feature. This means that instead of using the channel force field mentioned in Chapter 4, the obstacles have been used to provide more freedom for patients to move their hands within the work-space. Obstacles are being used for motion guidance (via force field) and they are the same objects as targets; based on provided force fields, their functionality can be changed. To the best knowledge of the author, this feature has not been studied in any previous research. Each of the objects (i.e. initial position, targets, and obstacles) was defined with different colors and shapes, which can be adjusted using the color setting button. Some patients are color blinded or have a vision impairment, so having an option to change the color and shape may help during the exercise adjustment [53, 59]. The time constraint for reaching the targets added to the GUI after obtaining the initial feedback from one occupational therapist prior to the interviews.

(c) The *Force strength adjustment:* In the exercise, each target and obstacle have a force around them; if an attractive value is put on the slider, the target/obstacle will have attraction effect and a repulsive effect if a repulsive force is set. The force around targets and obstacles can be adjusted two ways: 1) using a slider or 2) using a numerical down/up in the force strength adjustment panel. If therapists select zero for targets and obstacles in the force strength mode adjustment, the robot will not assist or resist patients' movements.

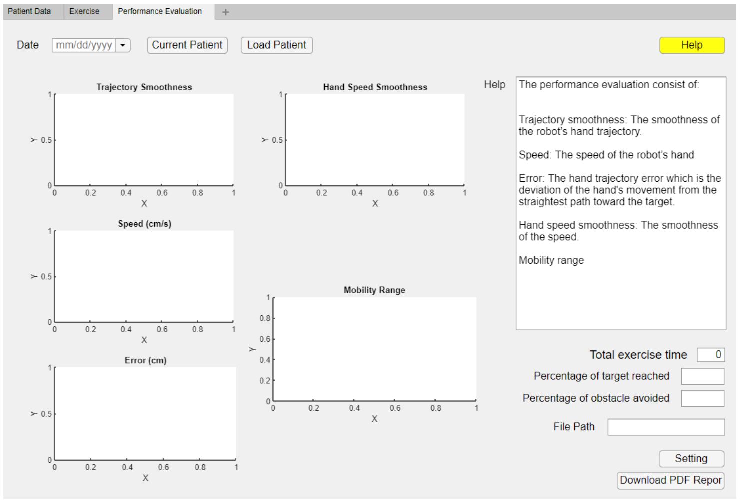
(d) The *force strength mode panel:* If therapists prefer the manual mode of therapy, they can adjust the strength of the forces manually in the force strength adjustment panel. If they decide to use the automated mode the robot will adjust the parameters based on the patient's performance from previous sessions. In addition, there is a semi-automated mode where they can increase or decrease the level of difficulty of the session compared to the previous sessions.

(e) The *help button:* This button is located at the top right. It explains every component and its functionality.

(f) The *Robot status panel:* In this panel, there is a lamp that indicates the robot's status, so if the robot is working the green lamb is on, if the robot is waiting for a command, the yellow lamp is on and if the robot in its stop mode, the red lamp is on.

(g) At the end therapists have access to three buttons for starting, pausing, and ending the exercise.

2. **The Performance Evaluation tab:** In this tab, therapists are able to have a performance evaluation report of the current patient or they can load another patient's data. The performance evaluation consists of:



The performance evaluation consist of:

Trajectory smoothness: The smoothness of the robot's hand trajectory.

Speed: The speed of the robot's hand

Error: The hand trajectory error which is the deviation of the hand's movement from the straightest path toward the target.

Hand speed smoothness: The smoothness of the speed.

Mobility range

Total exercise time 0

Percentage of target reached

Percentage of obstacle avoided

File Path

Figure 5.3: Performance evaluation section of initial GUI design

(a) The *trajectory smoothness*, which is measured as a function of changes in the end-effector's motion direction, specifically the least amount of deviation from the optimal trajectory toward the target. Lower smoothness value will be as a result of frequent changes in motion direction [53].

(b) The *speed of the hand* is the same as the speed of the end-effector [53], has been stated to be an important requirement in assessing the patient's performance during rehabilitation [56].

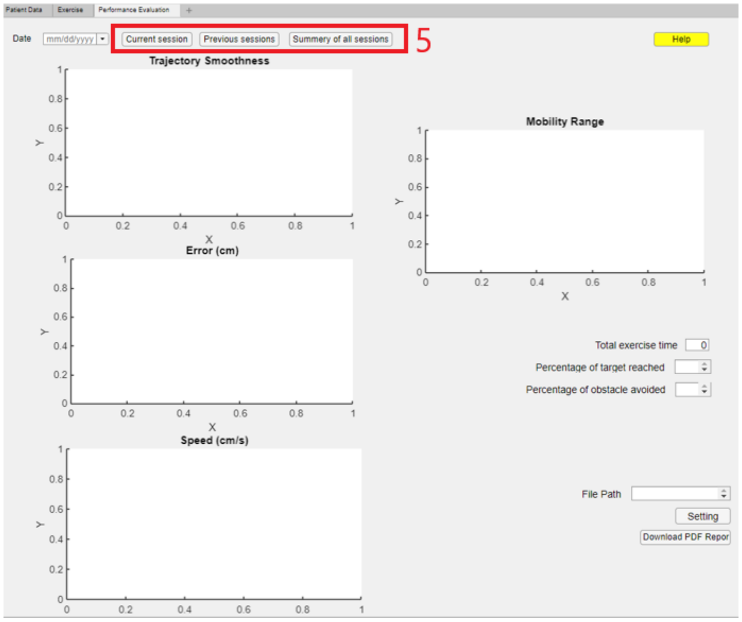


Figure 5.4: Performance evaluation section of the revised GUI design

(c) The *error* or (deviation) from the optimal trajectory towards the target [53].

(d) The *hand speed smoothness* indicates the smoothness of the hand speed (i.e., jerkiness of the hand movement) [3]. The occupational therapist who provided input stated that the efficiency of hand smoothness is important, however, therapists are not interested in temporarily jerky movements, therefore they may want to look at the speed smoothness.

(e) The *mobility range* indicates how far a patient can reach. Mobility range assessment is an essential part of post-stroke rehabilitation [21, 135].

(f) The *percentage of targets reached and obstacles avoided* is the percentage of targets reached and obstacles avoided out of the numbers of assigned targets

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[3] The jerkiness of the hand movement is quantified by obtaining the derivation of the acceleration in the duration of movement [102]

and obstacles.

(g) The *total exercise time* starts when the patient starts the exercise and finish when the patient end the exercise. The exercise time has been previously used in motor measurement [75].

After each session or in between them, therapists are able to download a PDF report of the information stated above for further data analysis.

5.3 First Interview

5.3.1 Method

Participants were recruited via a recruitment email that was sent out via the project team's networks and colleagues. This study received approval from the University of Waterloo's REB (Study Humans: 42508 "Collaborative design of a Graphical User Interface (GUI) for an upper extremity rehabilitation robot: Interviews with therapists").

The inclusion criteria for this study were:

1. Be a rehabilitation therapist.
2. Have a minimum of 1-year experience in stroke rehabilitation.
3. Be able to provide informed consent.
4. Be willing to allow the audio to be recorded for future data analysis.

5. Be able to communicate fluently in English

Prior to the interview:

1. Participants were recruited via email.
2. Participants were emailed an information sheet about the study. They were asked to let the student researcher know within two weeks if they were interested.
3. Participants who confirmed they were interested in participating were emailed a link to a zoom call at a mutually convenient time.

On the day of interview: One-on-one semi-structured interviews were conducted where open-ended questions were asked to guide the discussion between the student researcher and the participant. Semi-structured interviews are widely used in guided qualitative research [30]. The protocol guiding the interview was as follows:

1. The interview session began with the researcher verbally administered the consent questions (Appendix A) and demographic from (Appendix B) and record responses through a Qualtrics form that the researcher filled out using the person's ID code.
2. The interviews were recorded and were qualitatively analyzed by the research team to help the researcher improve the prototypes. Note: Only the screen along with the audio were video recorded (i.e., no faces or surroundings were captured).
3. Each interview session was 1.5 hours or less, including the study time and questionnaires.

The interview protocol for the first stage:

The interviews were conducted via zoom video using the following steps:

1. Introduction, getting to know each other, setting up the recording.
2. Explaining the purpose of the interview and the expected duration of the interview.
3. Presenting an introduction about the rehabilitation robot and its controller and asking participants if they have any questions; this has been followed by presenting the prototype GUI (Fig. 5.1 and Fig. 5.3).
4. Working through the open-ended questions outlined in interview questions (Appendix C)
5. Thank the participant for their participation, answering any questions they may have.

After obtaining the feedback from therapists, the research notes were used to create an affinity diagram to extract ideas for guiding revisions to the initial GUI design [117]. The affinity diagram is used for grouping the ideas and is a popular and powerful grouping method for performing qualitative data analysis and organization [49,61,93]. This method originally was introduced by Kawakita and has been used in brainstorming and planning [55], the method further adapted to analyze interviews and observational data [15]. The affinity diagramming method is usually performed with minimal support of technology, and the items/notes to be sorted are organized in a team-based on their affinity and are often recorded on sticky notes [49, 50]. For this research, the affinity diagram method was used to analyze interviews and the video recordings [15]. The ideas were grouped into

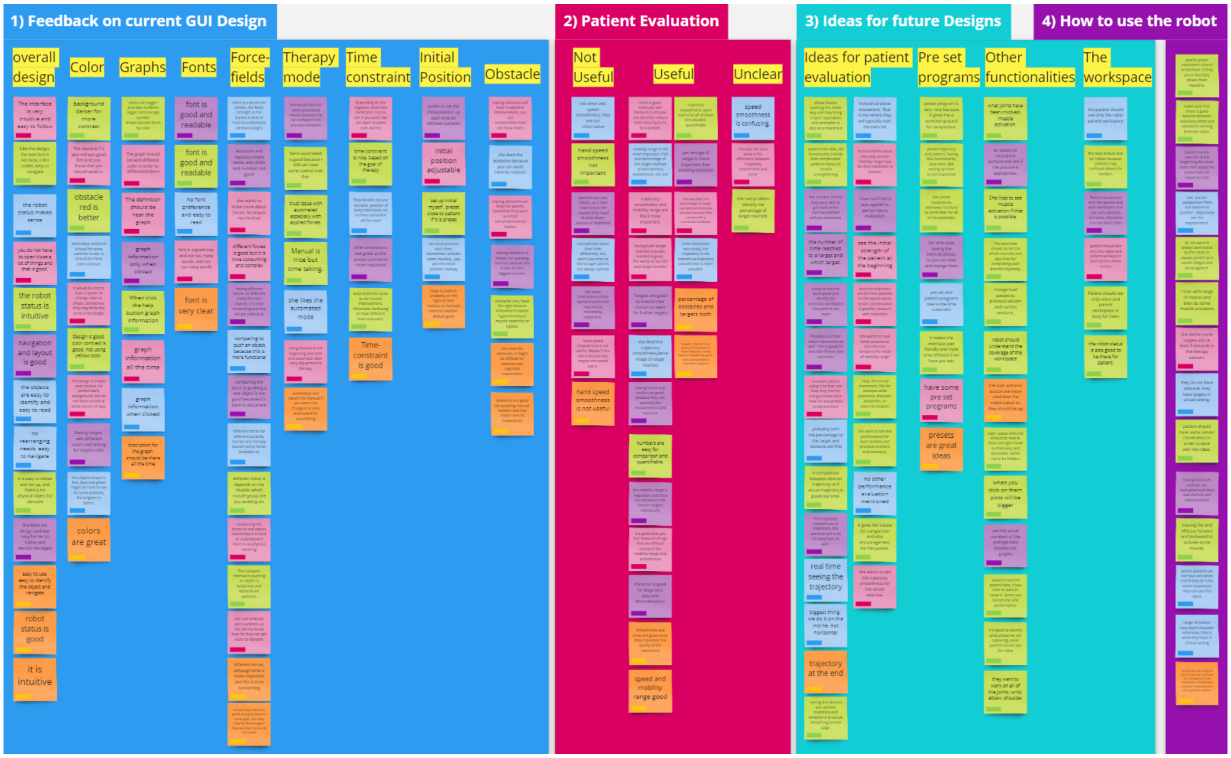

Figure 5.5: Affinity diagram created using Miro for the data from the first stage of interviews. The sticky note colors reflect individual therapists.

themes to reduce the feedback into similar and smaller groups of data, which helped in the data analysis and identification of key feature and function changes. Due to COVID-19 in-person meetings were not possible, therefore the research team used Miro (i.e., Miro is an online visual collaboration platform) to group the ideas based on their affinity. The final affinity diagram for the first stage of the interview is shown in Fig. 5.5.

5.3.2 Results

Five therapists participated in this research. They were physiotherapists (n=2), occupational therapists (n=3). The experience of participants regarding stroke rehabilitation ranged from 5 to 29 years (average = 13 years). The gender for all therapists was female. None of the participants had prior experience with rehabilitation robots. This convenience sample size aligns with those that have been used in similar research studies [26, 53, 114].

The 170 ideas extracted from the interviews were categorized into four main groups through the affinity mapping using Miro: 1) Feedback on current GUI design, 2) Patient Evaluation, 3) Ideas for future designs, and 4) How to use the robot. The elements of each theme along with key points and insights from the therapists are discussed below.

FEEDBACK ON CURRENT GUI DESIGN

Overall Design: All of the therapists liked the design of the GUI, they felt that the interface was intuitive and easy to use and navigate.

Color:

1. While all of the therapists liked the colors used for the GUI, they all mentioned that the setting button for changing the colors and shape of the objects is needed as some patients have vision impairments. In addition, they all mentioned they would like to see the targets with different colors.Also, three therapists mentioned they would like to have the red color for the obstacle.

2. Two therapists mentioned they would like to use an interface with a darker background as they do not want to work with a white or bright color background all day.
3. Two therapists mentioned they would like to see more color contrast for the patient and robot work-space.

Graphs:

1. Two therapists wanted the graph information always displayed in the performance evaluation tab and three therapists stated that they want to see this information only when they click the help button.
2. Two of the therapists wanted to see the plots and numbers bigger.
3. Three of the therapists wanted the graph information to be displayed with different colors.

Fonts: All of the therapists mentioned the fonts are easy to read.

Force-fields:

1. Three therapists mentioned the force-fields were hard to understand without using the robot first-hand. They wanted to see a more functional way to represent the force-fields like the way of comparing the force strength to pushing a real object in their everyday life. However, two therapists mentioned the comparison method would be hard to document and it is subjective based on each patient using it.

2. Four therapists mentioned they want to have different forces for different targets and obstacles to enable them to target different muscle groups. However, they mentioned having different forces for different objects is time-consuming to set up.

Therapy Modes: The therapists were presented with three conceptual modes: 1) *Manual* where the therapists adjust everything and values are static until the therapists changes them; 2) *Semi-automatic* where therapists adjust the level of the difficulty of the session relative to the previous session, and 3) *Automatic* where the robot adjusts the parameters based on the patient's performance from the previous sessions. Three therapists liked the idea of the automated mode of therapy, however, they mentioned they would not use this mode as they do not trust the robot with applied forces to work with patients alone. They mentioned they will mostly use the manual mode and sometimes they will switch to the semi-automated mode where they can still have some control over the robot. Two therapists mentioned that full manual mode may take time to adjust all the parameters and this could make it difficult to even provide the initial parameters' adjustments since there is no predetermined or predefined systematic approach to it. One of the therapists mentioned that the semi-automated is good because they can compare its numerical data with the previous session.

Time-constraint: Three therapists mentioned the time-constraint is good to use based on the patient's cognition level and exercise. On the other hand, two therapists mentioned using time-constraint is not good as the patients tend to rush and not use their best position of body mechanics and proper postural balance.

Initial Position: All of the therapists mentioned they want to set up the initial position themselves each time based on the practice that they want to have and the muscle group they want to work on. Moreover, two therapists mentioned if there is a default position for the initial position, they prefer to see it close to the patient and probably on the right of their mid-line (for right arm hemiparesis patients) to facilitate the external rotation.

Obstacles: All of the therapists liked the idea of having obstacles for inhibiting the compensatory motions; they mentioned avoiding the internal rotation is one of their biggest concerns, and with obstacles, the patients are able to avoid the internal rotation. They further mentioned having obstacles will help in the objective measurements, and as time passes, they would reduce the forces around the obstacle and they will see the result.

PATIENT EVALUATION

Not Useful:

1. All of the therapists stated the hand speed smoothness is not necessarily important. One of the therapists mentioned if the hand speed is not smooth, the trajectory will not be either, and the trajectory smoothness is more important than the hand speed smoothness.
2. Two therapists mentioned the speed information is not useful because if a patient's trajectory is not smooth, the therapist would want to slow down the movement so the patient has a better chance of maintaining the quality of the movement. In other

words, therapists felt the quality of the movement is more important than the speed of the movement.

3. One therapist stated that error information is not valuable because each patient moves their limb differently and the straightest path may not be necessarily the goal of therapy for each patient.

Usefulness:

1. All of the therapists stated that the mobility range and smoothness of the hand are the most two important performance evaluations.
2. The objective measurement was valuable for the therapists, they stated that they could use the information of the trajectory smoothness , error, mobility range, and speed for quantifying their data and documentation. The objective information could help them in understanding patient performance and providing feedback to interact with their patients.
3. All of the therapists wanted to see the percentage of targets reached and obstacles avoided; one therapist mentioned the percentage of target reached is more important than the percentage of obstacles avoided.

Unclear: Speed smoothness was confusing for all of the therapists. One of the therapists was not sure about the difference between the error and the trajectory smoothness. In addition, one therapist had a problem identifying the percentage of targets reached.

IDEAS FOR FUTURE DESIGNS

Ideas for patient evaluation:

1. The exercises should be functional; they should represent Activities of Daily Living (ADL) and the physiological terminology of the rehabilitation practices (e.g., flexion, extension, abduction, and adduction).

2. One of the therapists stated that she would like to see the number of times the patient reached a target and which target it was. In addition, she prefers to see the number of times the patient could reach the initial position without assistance. She further stated that having the performance evaluation on the way back from a target to the initial position is also important.

3. Two of the therapists mentioned that they prefer to run an initialization to identify the boundaries of the work-space before adjusting the exercise to determine the potential work-space of the patient and then adjust the exercise based on that.

4. Three of the therapists preferred to see the real-time of the actual trajectory and the desired trajectory and they wanted to compare those trajectories together. They preferred this option to be hidden if they do not want to use it and to be shown if they want to see it. One therapist wanted to see the trajectories only at the end of the session.

5. Two therapists mentioned they want to see the information represented as numbers in addition to graphs so they could compare the performance and use numbers for

the documentation. They also wanted to see the applied force strength numbers at the end.

Preset programs: All of the therapists stated that they want to have preset programs that they could load and adjust. They preferred to see these presets as a way similar to represent the ADL and the physiological terminology of the rehabilitation sessions. This would save time for them and makes the interface more user friendly.

Other functionalities:

1. One of the therapists mentioned that she would like to see what joints have been involved during the session and what was the muscle activation. She stated that usually in a rehabilitation session they want to engage all of the joints (i.e., wrist, elbow, and shoulder).
2. One therapist mentioned having an option to capture the posture is very important and can help therapists during the session.
3. Two therapists stated that they want to see the start, pause, and end exercise buttons close to the force strength mode, as that would be more obvious for them and it is easier for them to access it.
4. One therapist wanted the plots to be bigger if she clicks on them.

The work-space: Therapists preferred patients to see only "the robot and patient work-space" and not the rest of the screen, since it was thought that the other information would be confusing for patients.

HOW TO USE THE ROBOT

1. One therapist mentioned that when using the robot, she will make sure that there is a good balance between voluntary movement and the assistance coming from the robot, as she does not want the robot to be dominant all the time, neither the patient.
2. All the therapists mentioned that patients should have certain muscle activation to be able to work with the robot, they further stated that severely affected patients cannot work with the robot (because of the form-factor of the robot, not the GUI). In addition, they mentioned they will not usually do the planar movement a lot of time, instead, they do some other movements like inclining and moving their arms around in the different areas of the space.
3. Three therapists mentioned they would want to see the patient to move the end effector forward and backward to activate some muscles and then assign targets and obstacles for them.

5.4 Revised GUI Design

The GUI was revised based on the feedback from the first set of interviews. The recommendations received from therapists that were possible to implement were incorporated into the design. The five most significant changes were:

1. Robot and patient work-space colors were changed to have higher-contrasting colors. The space in the 1 rectangle in Fig. 5.2 shows the changes.

2. Targets with multiple colors were added in the exercise adjustment section of the GUI, as shown in the 2 rectangular shape in Fig. 5.2. Therapists stated they can navigate the patients through the targets using targets of different colors better compared to the situation that they have numbers on targets.

3. Color of obstacles was changed to red in the exercise adjustment section of the GUI as shown in the 3 rectangular shape Fig. 5.2. Therapists mentioned they would like to have obstacles red, as this color represents an object that patients should avoid.

4. Speed smoothness was removed from the performance evaluation section of the GUI as all the therapists stated that the data of speed smoothness was not useful for them. The updated version is shown in Fig. 5.4.

5. The current patient and load patient buttons were removed from the performance evaluation section. Instead, the current session, previous sessions, and a summary of all sessions buttons were added as seen in the 5 rectangular shape in Fig. 5.4. In the updated version, therapists have access to the data of the current session or they can choose the session data from the previous sessions button. Additionally, they are able to obtain summary data of all the sessions. Two therapists suggested the new buttons (i.e., the current session, previous sessions, and summary of all sessions buttons), and the buttons were added to further investigation with other therapists at the revised stage of the interviews. The updated version is shown in Fig. 5.4.

5.5 Second Interview

The interview questions guiding the second stage of interviews (outlined in Appendix D) were constructed based on the data received in the first stage of interviews and to capture data that explores the appropriateness of the revised GUI.

5.5.1 Methods

All of the five participants who participated in the first stage of interviews participated in the second stage of the interviews.

Interview protocol for the second stage: One-on-one semi-structured interviews were conducted using zoom video conferencing where open-ended questions were asked to guide the discussion between the student researcher and the participant. The interviews were conducted using the following steps:

1. The student researcher explained the purpose of the interview and the expected duration of the interview.
2. The student researcher presented a short overview of the robot and the revised prototype GUI (Fig. 5.2 and Fig. 5.4), set up the recording and asked the participants if they have any questions.
3. The student researcher and participants worked through the open-ended interview questions (outlined in Appendix D)

4. Participants were thanked for their participation and any final questions they had were answered.

After obtaining the feedback from therapists, excerpts from research study notes were sorted into two categories: 1) concepts therapists were agreed on and 2) concepts therapists were not agreed on.

5.5.2 Results

Concepts extracted from the second interviews that all five therapists agreed on were:

1. They liked the colors used for targets, obstacles, robot, and patient's work-space in the revised version of the GUI. However, one of the therapists stated that it might be hard to see the initial position object on the patient's work-space, as they both have a green color.
2. An ideal trajectory from one target to another target is a straight path (rather than a curved path). Therapists stated that the curved trajectory shows the muscle weakness if it is unintentional and if the curvature is intentional it requires more motor control.
3. As stated in the first stage of interviews, therapists preferred the patient to see only the robot and patient work-space and not the rest of the screen. In the second stage of interviews, all therapists preferred to hide even the axes of robot and patient work-space as well, as they stated that the axes are confusing for patients.

4. Therapists understood what is represented by the percentage of targets reached and obstacles avoided.
5. In the first stage of interviews, one therapist preferred to see the performance evaluation not only from the way toward the targets but also the way back to the initial position from targets. In the second stage of interviews, the therapists were asked about whether they would like this feature and all of the therapists said they would.
6. All therapists preferred the average, minimum, and maximum information of the graph data to be represented to the right side of the graphs.
7. Therapists agreed the revised performance evaluation design captured metrics they could use to evaluate their patients' performance. They envisioned that they would use the graph data and the data from the force strength adjustment panel to document their data and to be able to objectively measure the patient's performance.
8. All therapists were asked if the change in the button for the current session, previous sessions, and summary of all the sessions (showed in 5 in Fig. 5.4) was better or worse than the initial design; all therapists preferred the new option.
9. Fonts, graphs, and numbers were easy to read.
10. The therapists thought the GUI appeared to be user friendly and navigation seemed to be easy.

Concepts therapists were not agreed on were:

1. Therapists were asked if they would like to have access to all three methods of force adjustment (i.e. slider, numerical down/up, and comparing the force strength to pushing a real object). Three therapists preferred using the sliders and numerical down/up as they felt those methods are more intuitive and less subjective than the comparison method. However, two other therapists stated that they would like to use the comparison method as this method is more functional and intuitive for them. They stated that the force can be subjective but at least they have some idea of where the force at. They wanted this information to be shown as a text close to the force strength mode panel. One therapist mentioned as long as there is one example (e.g., -50 means pushing a glass full of water) it helps them to understand the force strength and they can figure out other forces from there.

2. Three therapists stated that they prefer to use the same force for each object in the same session, as assigning different forces for multiple objects is time-consuming and make the GUI less user friendly. On the other hand, two therapists mentioned they would like to use different forces for each object, as depends on the length of the session and they do not want the patient to do repetitive movements and get bored. In addition, assigning different forces for each object, helps them to work on the muscle group they want.

3. In the first stage of interviews, all therapists stated that they prefer the patients to see only the robot and patient work-space and not the rest of the screen. In the second stage of interviews, therapists were asked about the features of the GUI that patients would see. When therapists were asked if they want the patient to see the obstacles

during the exercise, two therapists stated that they do not want the patients to see the obstacle as this would be confusing for them, however, two therapists stated that they want the patients to see the obstacle as they should have some visual feedback. One therapist stated that she will hide or show the obstacles to patients depending on their level of cognition.

4. Therapists were asked about the patient's trajectory and if they wanted the patient to see their trajectory. Two therapists preferred to hide the trajectory for patients; while three therapists preferred if patients could see their trajectory as they stated the patients would benefit from visual feedback.

5. Three therapists preferred patients to see the robot status while two therapists stated that they do not want the robot status to be shown for patients as it causes more distraction.

6. All therapists were asked if they have any other comments regarding the GUI that patients will see. Two therapists stated that they do not want the patient to see the green and blue shaded regions of the robot and patients' work-space (shown in rectangle 1 in Fig. 5.2) as they are distracting for patients. One therapist mentioned a label should be presented in the robot and patient work-space to show the patients what is each object.

7. Four therapists were agreed that both the error and speed measurements in the performance evaluation tab are good and useful; however, one therapist mentioned the speed information is not necessarily useful, as the quality of movement is more

important than a faster movement. On the other hand, one therapist mentioned speed is important, as a patient may improve from having no movement to do a fast movement.

8. Four therapists preferred to run an initialization at the beginning of the exercise to identify the maximum space that the patient can reach and adjust the exercise based on that; however, one therapist mentioned if she knows the patient, she would already know how far the patient can reach so would not do an initialization.
9. Therapists were asked if they want to have other measurements for capturing the patients' performance. Four therapists did not mention any other measurements; one therapist preferred to see feedback on the trunk position of the patient.
10. Two therapists preferred the darker background of the revised GUI, especially for the performance evaluation tab where the only other color presented was the white used for the graphs. Three therapists preferred the light gray color.
11. Four therapists preferred the graphs to represent different colors and one therapist preferred the graphs to be shown with the same color.
12. Four therapists preferred the start, pause, and end buttons to be in the same place in Fig. 5.2. They stated that they will look at the GUI from top to down and left to right. One therapist preferred to see those buttons next to the force strength mode, as she imagined she would use those buttons more often and they are more identifiable there. She also stated that she preferred to see the robot status panel at the bottom.

5.6 Discussion

While the sample size of this research is small, there were trends that appeared through the collaborative design process used in this research. All the therapists who participated in this research mentioned that controlling internal rotation is one of the main concerns of upper-limb post-stroke rehabilitation. The obstacles added to the GUI design were intended to assist patients in avoiding specific regions assigned by therapists, which could help them to avoid movements such as internal rotation. The purpose of using obstacles and making them visible in the GUI can be different in terms of their functionality. Namely, if the obstacles provide a force field and promote a specific path, then making the obstacles visible might be counter productive because patients will not have the time to process their own intrinsic feedback to guide the performance. On the other hand, if the goal is to provide an explicit boundary for the movement (or to induce some variation from trial to trial) the obstacles can possibly be visible because it could promote patients to use their extrinsic feedback in order to perform (e.g. they learn to use the extrinsic feedback to guide performance rather than figure out how to get better). During the interviews with therapists, it was mentioned that having obstacles could not only support movement trajectory, but therapists could also use the numerical data of the obstacles' force strength to objectively measure patients' performance (e.g., as time passes, therapists will reduce the forces around the obstacles to see what happens). However, from the comments from therapists, the force strength numerical data was difficult for them to understand without actually using the robot. It was suggested that a description showing an example comparing the force strength values to the forces that they would experience when pushing real objects could be used to make the data more intuitive for therapists; this is an example of how to make values less arbitrary for the therapist end-users. Future research is needed to explicitly explore what method can be used to make the parameter adjustment of the robot more intuitive for therapists.

Due to COVID-19, in-person meetings were not possible, therefore therapists were not able to see or try the actual robot and the GUI. The exploration of GUI features was made based on virtual meetings. If in-person meetings were possible, some results would likely be different. For example, if therapists were able to use the robot and felt how the force strength changed when they adjusted it, the force strength adjustment panel might have been easier for them to understand. Regardless, it is reasonable for the therapists to use the method that feels most natural to them. This suggests that a GUI design for upper-limb rehab robots should have more than one way for therapists to control the robot settings (e.g., the slider plus numerical up/down value seen in Fig. 5.2).

The quality of the patients' movement is another important concern for therapists. Therapists stated they would use the trajectory smoothness and error measurement to qualify the patient's performance. Additionally, recommendations were made by therapists for addressing the quality of movements, including an ability to monitor the posture, ability to capture what joints are involved in the movement, and an ability to identify what muscles are engaged during the exercise. While these features were not investigated in this study, they have been studied in previous researches [68, 115, 120, 136]. These features are also possible to implement using the robot studied in this research, however this remains a topic of future research.

Speed smoothness is another qualitative evaluation method that therapists could use for evaluating the patients' movement smoothness that has been studied in other research [27, 102], however, all the therapists who participated in this study did not believe that the speed smoothness would be important. Regardless, most of the therapists mentioned they would need to work with the robot and explore these features before they could truly comment on their usefulness. Although this metric is quantifiable, it should be noted that the smoothness of a movement is the result of motor processes that operate below the level of consciousness, therefore consciously knowing its value would not necessarily help a the patient or therapist to make his or her movements smoother. This information could be used to complement the performance report on movement smoothness and to provide objective measurements. Thus, this research suggests further investigation of the speed smoothness as a way to qualitatively evaluate patients' movement.

Patients are also important users of the GUI. Through this research, it was found that the GUI that patients would use would likely be different from the one that therapists use. Therapists who participated in this study narrowed down the features that they thought patients should see in the GUI and stressed having a patient-GUI that was less confusing and not distracting. As the patient-design of the interface was not explicitly explored in this study and there were no patient participants, the patient-GUI should designed in future research with patients to identify what they would like to see and what is beneficial for them to see.

Three therapists stated that they do not trust an unsupervised robot with patients and they would not use the automated mode of therapy because of that. Trust is an essential element for successful human-robot interaction and previous studies have investigated this matter (e.g., [63, 70, 119]). Results from this thesis underscore the need for future research to explicitly explore the relationship of trust in how therapists use rehabilitation robots as well as how GUI and controller design can help to support trust.

It should be noted that during the interviews, there were some comments regarding the functionality of the exercises and if they can represent ADL. Based on the observational data coming from the research team, the robot is only designed to improve the range of motion with indirectly benefit functional ability but will not likely promote the type of skill learning needed to transfer to ADL. The robot is also arm centric, while many ADLs require some degree of fractionated finger movements. This means the robot is likely best suited to recover the range of motion and strength in the upper limb movement of stroke patients.

Limitations and methodological considerations

This study was primarily focused on what information therapists felt was best for robot control and understanding patients' outcomes; it did not consider how this information might impact promoting motor learning (e.g., whether the information should be provided/ how the information should be used). Specifically, the interviews focused on the GUI functionality not the optimal use of the GUI to maximize learning/recovery. From a motor learning perspective, not all the information included is going to promote optimal behaviors/ brain states for learning. Namely, if feedback is not done appropriately it can create a dependency on information that is not available outside the rehabilitation context, causing patients to not be able to (partially or completely) process their own intrinsic feedback to guide the movement [81]. Some of these issues are indirectly captured in the therapists feedback (e.g., their adverseness to smoothness of the speed).

There may be gender bias inherent in the data since all of the participants were female. Previously, researchers have investigated gender preference in interface design (e.g., [18,86]) and concluded that gender impacts the design of interfaces. However, as gender and interface design were not specifically examined through this work it is unknown how gender may have played a role.

The study group included physiotherapists (n=2) and occupational therapists (n=3). As the goals and rehabilitation approaches of physiotherapists and occupational therapists are not always the same, the groups might have different preferences for the mode of therapy and goal of rehabilitation session. However, the sample size of this research was too small to explore this; it is a question that needs to be asked in future work.

It is worth mentioning that the therapists who participated in this research had no prior experience with upper limb rehabilitation robots. It is unknown how the prior experience with the robot could have impacted results, particularly as all interviews were done remotely without the therapists being able to try out the robot. However, as this research aims to create a GUI that is intuitive for therapists with no prior experience, data from the therapists in this research provides a insight into first impressions of naive users.

Therapists ranged from 5-29 years of experience, which may have caused differences in their opinions regarding the GUI design. For example, when therapists were asked about the method that they want to use for adjusting the force strength, the therapist who had the most years of experience (i.e., 29) stated that while the younger therapists preferred the slider option, she preferred a method that she can compare the force strength to the force that she would use for pushing a real object in her real-life . It would be valuable to investigate in future work how experience and age may play a role in preferences and how therapists use the GUI.

The sample size in this research was small (n=5). A small sample size may prevent the result of a study to be extrapolated or generalised and a big sample size could enable statistical differences to be identified [32]. All the therapists were from the same geographic region; the the exercises that therapists use for their patients and other differences in training and best practice may be different from one region to another. Results from this research work underscore the need for future research to explicitly explore the GUI using a bigger sample size that includes therapists from other geographical regions.

5.7 Chapter summary and key points

This chapter described two stages of interviews and iterative design with rehabilitation therapists to create an intuitive GUI for therapists to enable them to control the upper limb rehabilitation robot showed in Fig. 3.1. Key findings from this research are:

1. Including obstacles in the exercises could help patients to avoid specific regions (i.e., support movement trajectory) and avoid internal rotation.
2. Force-field method might be a possible useful method for supporting patients' movement trajectory, not only because therapists can adjust the force strength to suit

a specific patient, but also because they can use its numerical data for objective measurement of patients' performance.

3. The GUI that is designed for therapists might be different from GUI that is designed for patients. While therapists may prefer simpler designed GUI for patients as it would be less confusing and less distracting for them, further studies with patients to address the features they would like to see in the GUI needs to be investigated.

4. Trust is an important issue when human-robot interaction is considered. Further study could be conducted to explicitly investigate the trust issue in human-robot interaction and it may further help to achieve the success of human-robot interaction.

5. The quality of the movement is very important to therapists and appears that the different measurements stated in this research (i.e., trajectory smoothness, and error) could be used by therapists to evaluate it.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

The work described in this thesis shows how a dynamic model of the 2 DOF planar robot was obtained from the principal of virtual work and was verified using MapleSim software. The results showed that the derived dynamic model appears to be is valid and was therefore used as the basis for designing a the motion and force-field control and for the robot.

This research further shows how two control strategies, namely, motion and force-field control, could have benefits depending on the type of patient and the severity of the impairment of motor control due to stroke. Fig. 4.14, depicts the possible usage of each algorithm depending on the patient type. A novel adaptive algorithm was also proposed for fine-tuning the proposed force-field parameters based on the performance of the patient during the therapy. Due to COVID, the algorithm was validated using a simulated patient going through therapy sessions and the results suggested that the force-field algorithm has a positive effect on motor control recovery. The simulation also indicated that the resistive mode of therapy could result in better outcomes after the therapy, which agrees with observations in experimental studies by other researchers [38, 96]. This suggests the force-field control method that is proposed and implemented in this research is a promising approach to controlling end-effector rehabilitation robots; however, the true effectiveness will need to be evaluated on real patients in the future.

This work performed an iterative design process with rehabilitation therapists to create an intuitive GUI for therapists to enable them to control the upper limb rehabilitation robot. The identification of features and feedback on the intuitiveness of the GUI developed in this research highlights the value of collaborative design between engineers and therapists to create the interface that enables therapists to control the rehabilitation robot. This research identifies the need for collaborative GUI design with patients, as their needs and preferences may be different from therapists. During the collaborative GUI design, it was observed that including obstacles and force-field method might be a useful method for supporting patients' movement trajectory, not only because therapists can adjust the force strength to suit a specific patient, but also because they can use its numerical data for objective measurement of patients' performance. Therapists who participated in this research stated that objective measurements (i.e., trajectory smoothness, speed, mobility range and error) could be used to evaluate the patient performance. While rehabilitation robots are different in terms of mechanical structure, work-space, and the exercise that they can provide, similar methods could be used for supporting patients' movement trajectory and performance evaluation.

6.2 Future Work

The results given in Chapter 4 were limited by the accuracy of the patient model provided in Section 4.2.3. Therefore, as future work, the effectiveness of the proposed algorithm has to be further investigated in both resistive and assistive modes of training by implementing the algorithm on the robot and testing with therapists and patients. While the results of the study given in Chapter 4 suggest that patients may experience after-effect benefits from the use of the force fields, the possible slower rate of motor-learning in stroke patients compared to healthy subjects was not investigated in the patient model. Also, the psychological effects of the therapies on the patient may affect the performance of the patients, which was not studied in this research. Thus, future research should take these concepts into consideration.

This study focused on the robot control and the collaborative GUI design with therapists. However, *how* to be best implement the controller and GUI from a motor learning perspective is not addressed and should be in future work to maximize the benefits of the robot guided interventions. One principle of motor learning that as future work can be studied is the focus of attention. Focus of attention can either be internalized (focus on body's movements) vs. external (focus on outcome of body's movements). The internalized focus of attention could be watching the arm movements with our robot whereas the externalized focus of attention could be moving the robot arm and see the results real time in robot and patient work-space of the GUI. It is important to know that in this research, there has been no exploration in terms of internal versus external focus of attention and how they may impact the recovery outcomes, including how they might be mapped to complement different types of stroke. These questions must be explored so that the robot control and GUI used are better aligned with what promotes recovery for different stroke populations.

In the GUI design, future research is needed to explore what method can be used to make the parameter tuning of the robot more intuitive for therapists. Although therapists who participated in this study preferred a GUI with a simpler design to be shown specifically to the patients, the GUI should further be designed with patients to identify what they would like to see and what is beneficial for them to see. Results from this thesis work underscore the need for future research to explore the relationship of trust to how therapists use rehabilitation robots, as well as how the GUI and controller design can help to support trust. It would also be valuable to explicitly investigate how experience, age, gender, and geographical regions may play a role in preferences and how therapists use the GUI.

Research needs to be done on not just how to design the robot's controller or its GUI, including weather they complement motor recovery appropriately, but also on how using a robot impacts the rehabilitation program. While robots have potential to be useful, they have potential to be misused, using in a wrong context, or using inappropriately, which could cause irrecoverable harm. Collaborative work needs to be done to ensure engineers and therapists understand and disseminate how use the robot correctly and appropriately. It is also important to further explore how therapists use the performance metrics to provide feedback and when and what metrics should actually be used in this process. Augmented feedback can be quite an effective tool to promote learning, but only if employed correctly; if used inappropriately, feedback can produce a negative outcome in terms of functionality.

It needs to be explored how the robot could provide patients with a form of feedback that is not available to them during the everyday activities that the therapists are looking to transfer the robot-training to. This feedback could be visual, such as the axis of the robot and patient work-space, or the color shaded work-space of the robot or the patient.

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APPENDICES

Appendix A

Consent Form

Participants' Code

Enter the participant code below:

Consent Form

Consent Form for Rehabilitation Therapists

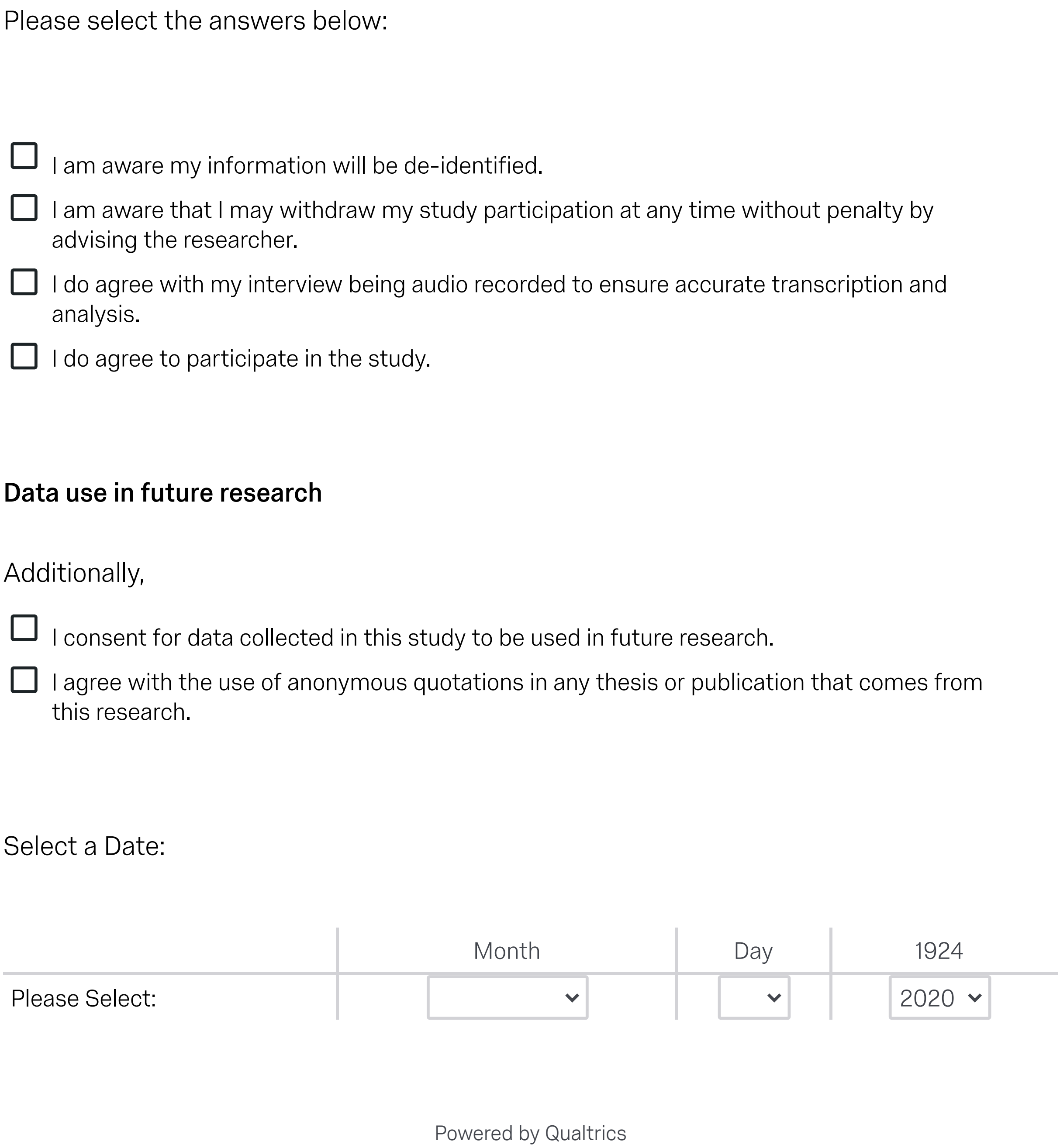
The following questions will be verbally asked at the beginning of the interview regarding your consent:

By signing this consent form, you are not waiving your legal rights or releasing the investigator(s) or involved institution(s) from their legal and professional responsibilities.

This study has been reviewed and received ethics clearance through a University of Waterloo Research Ethics Committee ORE #42508. Should you wish to contact the Office of Research Ethics, you may do so at 1-519-888-4567 ext. 36005 or ore-ceo@uwaterloo.ca.

The interviews will be recorded. Note: Only the screen along with audio will be video recorded (i.e., we will not be capturing any faces or their surroundings). The purpose of recording is for post-study data analysis. Your identity will not be revealed when used in publications or presentations.

I have read the information presented in the information letter about a study being conducted by the research team as part of Parya Khoshroo's Master thesis led by Dr. Jennifer Boger and Dr. John McPhee from Systems Design Engineering at the University of Waterloo. I have had the opportunity to ask any questions related to this study, to receive satisfactory answers to my questions, and any additional details I wanted.



Please select the answers below:

- ☐ I am aware my information will be de-identified.
- ☐ I am aware that I may withdraw my study participation at any time without penalty by advising the researcher.
- ☐ I do agree with my interview being audio recorded to ensure accurate transcription and analysis.
- ☐ I do agree to participate in the study.

Data use in future research

Additionally,

- ☐ I consent for data collected in this study to be used in future research.
- ☐ I agree with the use of anonymous quotations in any thesis or publication that comes from this research.

Select a Date:

	Month	Day	1924
Please Select:			2020

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Appendix B

Demographic Form

Default Question Block

Demographic Form

The study aims to iteratively develop and evaluate the GUI with rehabilitation therapists to create a GUI that is easy and intuitive for therapists to use to control the robot.

This is a strictly confidential questionnaire. Only a randomly generated participant ID number, assigned by
the research administrator will be on this questionnaire.

All data will be securely stored in password-protected lab servers of the principal investigators and access will be restricted to the research team. Your name will not appear in any report, presentation, or publication resulting from this research.

Thank you in advance for your valuable time!

Please type the participant code here:

What type of therapist/role in therapy describes you?

How many years have you been involved with stroke rehabilitation?

Do you have any prior experience with rehabilitation robots? If so, please specify.

Gender

○ Male

○ Female

○ Prefer to self identify

○ Prefer not to say

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Appendix C

Interview Questions for the 1st Stage

Table C.1: Interview Questions, 1st Stage.

Sub-stage	Topic	ID	Questions
Introduction	Introduction to robot and its controller	1	Have you ever worked with any types of rehabilitation robots before? - If yes, when and for how long? What was the type of robot? Upper-limb or lower-limb?
Exploring the GUI: Exercise adjustment	First Impression	2	What are your first impressions of the GUI?
	Robot & User Workspace Target, initial position, obstacles	3	a) Please identify where the following are on the GUI for me: a. the target b. obstacles c. initial position b) How would you use these things (targets, obstacles, initial position) in a therapy session? c) Would you like to see the default starting position close to the patient, midway to the target, or somewhere else? Or would you prefer to set the starting position yourself? d) Would you like to have a set of presets or pattern of targets and obstacles that you can load and adjust? Or would you prefer to set them up yourself each time? e) Would you like all the targets to have the same attraction/repulsive force? Or would you prefer each target to have different force? f) What do you think about the use of obstacles? Why? g) Would you like to be able to specify a time constraint for reaching to a target? Would you like to be able to change this time-constraint to be adjustable during the exercise?

	Exercise mode and force-field adjustment	4	a) What do you think about setting attraction/repulsive forces for the robot? Would you prefer the negative/positive method? b) What would be the most intuitive to you for the force-field adjustment? E.g. using slider/numerical down or up/ using another method like comparing the strength to pushing an object c) What do you think about the automated and semi-automated modes? Would you change anything about them? d) Would you like to be able to see the patient's trajectory as he/she moves the robot's hand, or you want to see it at the end (i.e., after the session is done)? e) Does the way the status of the robot is displayed make sense? and if not, what would you like to see done differently?
Exploring the GUI: Performance evaluation	Performance evaluation/ smoothness/speed/error	5	a) In your own words, please describe what each of the followings are; what information do they give you: a. Trajectory smoothness b. speed c. error d. Hand speed smoothness e. mobility range f. percentage of target reached b) Would you prefer another method of evaluation? If so, what? c) Would you like to see the hand trajectory error as part of performance evaluation? Is this information valuable to you? Why? d) Would you prefer to see the information describing the different evaluation data always displayed or you would like to see them only when you click the help button? e) Would you like to see a score for reaching to the targets, avoiding an obstacle, or both? What would you like this score to look like? f) Would you find this information in supporting your management of your clients? Why?

			a. (If answer to the above is "yes") How would you use these data? g) What information or data would you like to see at the end of session as a report of patients' performance?
Overall design	Overall design/fonts/colors/ navigation	6	a) Overall, what do you think about the design? b) Do you think the design is too plain, too colorful, or just right? If you would make any changes, what would they be? Would you change the background color of the screen? c) Would you prefer another font? If so, do you have a preference? d) Is the font size too large, too small, or, about right? e) Would you like to be able to change the color or shape of initial position, targets, and obstacle? Are there colors would you prefer for them? f) Would you like us to rearrange the layout? In other words, would you like to see things in a different place on the GUI? g) Is it easy for you to navigate between parts? If not, what would you like to see to make it easier for you?
Overall experience	Overall experience	7	a) Were there any features you would like to see in the GUI, but were not present in the design today? If so, what? b) Were there any features you did not like? If so, what were they and why? c) Were there any features that you liked? If so, what and why? d) Is there anything else you would like to share?
Conclusion	Wrap up	8	Before we finish, do you have any additional comments or questions about today's session?

Appendix D

Interview Questions for the 2nd Stage

Table D.1: Interview Questions,2nd Stage.

Sub-stage	Topic	ID	Questions
Exploring the GUI: Exercise adjustment	First impression	1	What are your first impressions?
	Exercise mode and force-field adjustment	2	a) Would you like to have access to all three methods of force adjustment, i.e. slider, numerical down/up, comparing the force? b) Would you like to have different forces for each of the targets and obstacles that are being used in the same session? c) What is would be the desired/ideal trajectory from one target to another target? Is it a straight path, curved path, or something else? d) Does reaching for a target with or without obstacles mimic exercise(s) you do with patients? i.e. shoulder, elbow, wrist extension/flexion -abduction/adduction? e) We heard from therapists that they would like to know how the force compares to pushing an everyday object. Would this information be useful to you? If so, how would you want to see it? (i.e., force 10 N means pushing an empty plastic cup, 30 pushing an empty glass, 50 a glass full of water, and so on). This information can be represented either as separate keys or as information in the help button.
Exploring the GUI: patient GUI	Information about the GUI that patients will see		a) Would you like to hide the axes in the workspace that the patient will see? b) Would you like to hide obstacles in the patient's GUI? c) Would you like to hide the patient's trajectory in the patient's GUI? d) Would you like the robot status to be shown for the patients? e) Are there any other comments you have about the patient view?
Exploring the GUI: Performance evaluation	Performance evaluation	3	a) Would you like to have error and speed information as to performance evaluation information? b) Does the "percentage of targets reached" make sense to you? What do you think it means? c) Would you like to have the evaluations for the way back to the initial position as well, or only for the way toward the targets? d) Would you like to assess the patient's workspace at the beginning of the session? (i.e. moving around the robot's hand to see how far the patient can reach) and then adjust the exercise based on that? Or would you like a set workspace that reflects the maximum of the robot? Or something else? e) Would you like to see the numerical data of the graphs as well? If so, what numerical data you would like to see?

			f) Does the patients' performance evaluation capture metrics you that would be helpful for you to know? g) Is there any information or data that you would want to see in the patients' performance evaluation that is missing? If so, what? h) Would you like to have access to performance evaluation for the current session, previous sessions, and a summary of all the sessions?
Overall design	Overall design/ navigation/font	4	a) Would you prefer a darker background or the one presented in the light gray color? b) What do you think of the colors used for the initial position, obstacles, and target? Are there different colors you would use? c) What do you think about the color of the patient and robot workspace region? d) Would you like to have a setting for customizing the color and shape of the obstacles, targets, and starting position? e) What do you think about the multiple targets with different colors? f) Are the plots and numbers easy for you to see and read? g) Would you prefer graphs that use different colors or all use the same color? Which color (s) would you prefer? h) What do you think about the start, pause, and end button close to the force strength mode panel? Is it now more identifiable for you? i) Would you like us to move any section to another section? j) Is it easy for you to navigate between the different parts?
Overall experience	Overall experience	5	a) Were there any features you would like to see in the GUI, but were not present in the design today? If so, what? b) Were there any features that you particularly liked? If so, what? c) Were there any features you did not like in the updated version? If so, what were they and why? d) Is there anything else you would like to share?
Conclusion	Wrap up	6	Before we finish, do you have any additional comments about today's session or questions for me?