Development of a Portable Robot and Graphical User Interface for Haptic Rehabilitation Exercise

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Abstract—This paper presents progress in the development of a robotic system for post-stroke upper limb rehabilitation. It is a portable, lower cost, actuated upper limb robotic rehabilitation device, which is being developed to meet the needs of stroke therapists and their patients. The developed system provides force feedback for haptic rehabilitation, applying both resistive and assistive forces for more targeted exercises for post-stroke patients. The proposed system includes a graphical user interface with both manual and automatic control of the robotic device for upper limb exercise. The automatic control makes use of artificially intelligent systems to adapt the treatment with minimal interventions of therapists. It also provides virtual rehabilitation games for stroke patients. A focus group study with therapists was conducted to assess the developed system. Additionally, individual therapist sessions are in progress to further develop the graphical user interface and virtual reality games. These and other planned studies will offer valuable insights of therapists and stroke survivors for the further development and commercialization of the robotic system.

I. INTRODUCTION

Every year stroke affects 16.3 million people worldwide. It is the leading cause of permanent disability in adults [1]. Among those who have experienced a stroke, there are an estimated 64.5 million stroke survivors who live with varying levels of disability and need assistance for activities of daily living (ADL) [1]. Approximately 80% of these have motor deficits, resulting in serious disability [2]. The burden of care for stroke survivors is high for the healthcare system and family members or caregivers [1], [3].

Often the upper limb is impaired as the brain artery responsible for blood flow to areas controlling the upper limb is frequently involved in a stroke [4]. Therefore it is important for the upper limb to be supported and rehabilitated to perform ADLs, such as eating, bathing, and dressing.

Rehabilitation robots have been developed to alleviate the burden on therapists and healthcare systems, while simultaneously increasing patient access to rehabilitation. Several studies have shown similar improvement in stroke survivor outcomes with the use of rehabilitation robotic devices (RRD) when compared with conventional therapy [5], [6], [7]. RRDs are able to offer treatment features that would be difficult to achieve with conventional therapy [8], [9]. Features such as exact repetitive movements, programmable resistance levels, objective evaluation, and movement sensing capabilities could increase the value of RRD and hence clinical acceptance. Although robots will likely never replace therapists, they may be useful in aiding therapists or extending rehabilitation to remote locations or to the home.

There exist several robotic devices for upper limb post-stroke rehabilitation [7], however, most of the systems are not portable enough for home use or high costs restrict them to specialized clinics. As a result, the concept of extending rehabilitation to a remote location by optimizing the engineering design of the robot still remains an ongoing research topic in rehabilitation engineering. Hence, the main challenge is in determining the best clinical efficacy for the least amount of robotic complexity and functionality.

There are several control approaches to robotic therapy [10]. For example, a self-adaptive robot training method is described in [11] where the system assists a user to complete a tracking task using a minimal assistance strategy. A decision theoretic approach is described in [12] where an intelligent system autonomously controls the resistive force and target position to improve forward reaching capability of a stroke patient. The robotic therapy also employs virtual reality (VR) to engage the patients in repetitive motion exercise using 2D or 3D games [13]. Hence, the robotic systems make use of VR games to engage and motivate users with fun and meaningful activities [7]. The effective rehabilitation games are adapted to accommodate disabilities, gradable for improving abilities and provide appropriate feedback to enhance performance and encouragement.

With consideration of existing robotic systems and control techniques, this work has three objectives:

1) To develop a portable robotic system with a haptic interface that facilitates the concept of rehabilitation at a remote location, e.g., at a home.

2) To develop a graphical user interface (GUI) that integrates different control techniques and VR games in the same screen, and allows therapists to easily interact with the system.

3) To evaluate the current system with therapists in a focus group study.

This work addresses all three objectives mentioned above and develops a portable 2D haptic robotics system for upper limb stroke rehabilitation. It also develops a GUI that includes manual and automated haptic exercise as well as VR games for rehabilitation. Furthermore, a focus group and individual sessions are conducted to obtain therapist feedback on possible future improvements to the robotic system.

The rest of the paper is organized as follows. Sections II and III describe the robotic device and GUI. Section IV presents therapist feedback on the developed system.
V outlines the future work directions and finally, Section VI summarizes this work.

II. ROBOTIC SYSTEM

A. Method

The robot has been developed using a user-centred approach [14] which includes an international survey of therapists [15] to identify the design requirements of the robotic device. The development process also included our experiences with a previous prototype [16]. The detailed robot development steps can be found in [17]. The robotic device has been manufactured by Quanser Inc., a robotics company in Markham, Canada.

B. Device Description

The upper limb stroke rehabilitation robot prototype is a two degrees of freedom (2DOF) impedance controlled planar haptic robotic device (see Fig. 1(a)). The robot’s casing dimensions are approximately 32x14x39cm and its weight is about 17.3kg. Two DC motors attached with optical encoders drive the robotic arm through a capstan. The robotic arm is connected to a plastic end-effector, which is controlled by a patient during a rehabilitation exercise. The maximum force that can be applied through the end-effector using a motor of the robot is 52.8N. The optical resolution at the end effector is 0.013 mm/count at home position. This end effector is customizable for different patient requirements.

The robot is equipped with a tethered and movable external emergency stop to shut off power for safety purposes. The robot has a USB interface with a computer which makes it possible to operate the robot with a laptop or tablet device.

The robot is operated by QuaRC (Quanser’s Rapid Control Prototyping) software and it can be used with other programming languages using standard communication protocols, e.g., TCP/IP and shared memory.

C. Forward Kinematic Model

The forward kinematic model (FKM) of the robot is described using the two link manipulator model shown in Fig. 1(b), where the arm (link) lengths are defined as $L_1$=254 mm and $L_2$=266.7 mm. The link angles with x-axis are defined as $\theta_1$ and $\theta_2$. The geometric design criteria of the robot body imposed the following constraints on $\theta_1$ and $\theta_2$.

\[
\begin{align*}
\theta_1 &> \theta_2 \\
140^\circ &\geq \theta_1 - \theta_2 \geq 40^\circ \\
90^\circ &\geq \theta_1 \geq -50^\circ \\
50^\circ &\geq \theta_2 \geq -90^\circ
\end{align*}
\]

Eqns. 5-6 describe the FKM of the robot and Eqn. 7 shows the Jacobian matrix.

\[
\begin{align*}
x &= L_1 \cos \theta_1 + L_2 \cos \theta_2 \quad (5) \\
y &= L_1 \sin \theta_1 + L_2 \sin \theta_2 \quad (6) \\
J &= \begin{bmatrix}
-L_1 \sin \theta_1 & -L_2 \sin \theta_2 \\
-L_1 \cos \theta_1 & -L_2 \cos \theta_2
\end{bmatrix} \quad (7)
\end{align*}
\]

The kinematic equations result in the robot workspace shown in Fig. 2.

D. Haptic Effect

The haptic effect is applied using Eqn. 8, where the force, $F = [F_x \ F_y]^T$ to be applied on the end-effector is converted into torque, $\tau = [\tau_x \ \tau_y]^T$ and then the corresponding current, $I = [I_x \ I_y]^T$ is applied on the motors. The torque amplifying factor of the capstan is denoted as $K_a=30$ and the torque constant of the motor is found $K_t=0.115$ N-m/A from the motor specification.

\[
\begin{align*}
\tau &= -J^T F \quad (8) \\
I &= \frac{\tau}{K_a K_t} \quad (9)
\end{align*}
\]

The following force model is used to create the haptic effect.

\[
F = F_g - F_d + F_s = F_g - K_d V + K_s P \quad (10)
\]

Here, $F_g = [F_{x,g} \ F_{y,g}]^T$ is a constant global force, $F_d = [F_{x,d} \ F_{y,d}]^T$ is the damping force which is proportional to the end-effector velocity ($V = [V_x \ V_y]^T$), and $F_s = [F_{x,s} \ F_{y,s}]^T$ is the stiffness effect which is proportional to the position vector of the target ($P = [P_x \ P_y]^T$) with respect to the end-effector. The proportional constants $K_d$ and $K_s$ denote the damping and stiffness coefficients, respectively.

III. GRAPHICAL USER INTERFACE (GUI)

Fig. 3 shows the GUI developed for the robotic system. Fig. 3(a) depicts the control interface for the therapists and Fig. 3(b) shows the resizable visual feedback interface for their patients. The visual feedback interface shows real-time positions of the robot end-effector and target using a circle and rectangle, respectively. As the patients may have vision impairment, the feedback window also provides options for changing colors of the end-effector, target, and...
background to match patients’ visual capability. The overall exercise duration is also shown in the bottom-right corner of the visual-feedback interface. The GUI includes therapist interfaces for both manual and automatic haptic exercises. For each exercise it shows exercise information for performance evaluation. It also provides games that employ VR for encouraging the patients to be engaged in the repetitive motion exercises. A preliminary version of the GUI and VR games were evaluated by an experienced neurorehabilitation therapist (Dr. Debbie Hebert, Toronto Rehabilitation Institute). Changes were implemented as a result and presented here as follows.

A. Haptic

Fig. 4 shows the haptic interface, where therapists can select different force control parameters of the robot. A patient can perform an exercise with or without force feedback which is set by the Haptic (touch) feedback panel. An exercise with force feedback can further set force type, which is either resistive or assistive. The Resistance panel specifies different resistance levels equivalent to pushing different objects in real life, e.g., resistance equivalent to pushing a hard cover book is set approximately to 5N. Resistance is implemented as damping force which is proportional to end-effector speed and directed opposite to its velocity, i.e., Eqn. 10 uses $F_d = [0 \ 0]^T$, $F_s = [0 \ 0]^T$, and $K_d > 0$. Hence, the Resistance panel sets a different damping coefficient $K_d$ (N.s/m) corresponding to pushing each object.

The Assistance panel specifies three discrete levels of assistance, namely, Low, Medium, and High, for helping a patient to perform exercises. The robotic device generates an attractive force proportional to the distance between the end-effector and the target position for assisting the patient to reach the target points, i.e., Eqn. 10 uses $F_d = [0 \ 0]^T$, $F_s = [0 \ 0]^T$, and $K_s > 0$. The magnitude of the attractive force is clipped to three different levels, 3N, 7N, and 12N, corresponding to Low, Medium, and High spring constant $K_s$ (N/m) options in the Assistance panel.

B. Workspace

Fig. 5 shows the robot workspace in white. It also shows the current end-effector position as a red circle. The gray region inside the workspace denotes user-space, which shows the maximum distance from workspace-center at any direction covered by the patient in an exercise session. This interface is also used to set a target position to be reached by the patient. The button shown below the Set Target panel is used to start an exercise.

C. Performance data

Fig. 6 describes the performance data shown in the GUI. Fig. 6(a) shows the real-time exercise data which include instantaneous speed of the end-effector, error (deviation) from the optimal path towards the target, and smoothness of the end-effector trajectory. Smoothness of the trajectory is calculated as a function of change in the end-effector’s motion direction. Frequent changes in motion direction result in lower smoothness values. The GUI provides plots of average statistics of exercise data. It includes a pie chart of targets reached and missed in an exercise, average velocity, root-mean-square (RMS) error, and trajectory smoothness to reach each target in an exercise. The exercise data can be saved as session data where speed, error, and smoothness are averaged over all targets used in an exercise. This session data can be compared with future data for performance analysis over time. For example, Fig. 6(c) shows a comparison of average speed obtained from three different sessions for a patient.
D. Manual exercise

The GUI provides a manual mode of exercise which indicates direct supervision of movement exercise by a therapist. In this mode, the therapist sets the force parameters and target locations, and decides when to stop an exercise. There are two options available for performing a supervised exercise: 1) Interactive and 2) Waypoint. These options are described below.

1) Interactive exercise: This mode of exercise can be performed with or without a target position. In the absence of targets, the patient randomly moves the end-effector inside the robot workspace. The user-space is also updated with this movement. Different haptic effects can be applied on the end-effector during the movement. For example, Fig. 7(a) shows an instance where the exercise is performed without any target and a resistance equivalent to pushing 5 hard cover books is applied on the end-effector. In the case of assistance without a target, the system applies force towards the current motion direction of the end-effector, i.e., Eqn. 10 uses $F_g = [0 0]^T$, $F_s = [0 0]^T$, and $K_d < 0$. Fig. 7(b) shows an example of goal directed exercise where a target position is specified (green rectangle) in the workspace to be reached by the patient. In this example, Low assistance is also applied to help the patient to reach the target position. Note that the user-space (gray region), which is updated with the robot movement, can play an important role in a supervised exercise. A therapist can assign a new target position outside the user-space to extend upper limb mobility of a patient.

2) Waypoint exercise: In this mode of exercise, a therapist can define a set of target positions (or waypoints) to be reached by a patient following a predefined sequence. The therapist also sets a resistive or assistive type of force and a time constraint to reach each target location. The Haptic (touch) feedback panel is used to specify the force type and the Set Target panel is used to define the waypoint position (blue rectangle) and the time constraint (see Fig. 8(a)). Fig. 8(b) shows a result of a waypoint exercise where four waypoints are specified at four corners (green rectangles). The patient started from the workspace-center and followed an anti-clockwise sequence from the top right waypoint and finally returned to the starting waypoint. Waypoint exercise can play an important role in some cases where a therapist initially helps the patient to follow a trajectory for very low level recovery of the affected post-stroke upper limb.

E. Automated exercise

In this mode of exercise a therapist only defines a set of target locations and their associated time constraints. An intelligent system autonomously applies assistance or resistance to the end-effector and repeats the same target locations until the patient becomes fatigued. Unlike manual mode of exercise, the intelligent system decides when to stop an exercise based on patient fatigue. Fatigue is estimated as a function of end-effector speed and error to reach each target location. Fig. 9(a) shows an example of an automated forward reaching exercise. Fig. 9(a) shows the target locations (blue rectangles) and the updated user-space generated by the end-effector movement. Fig. 9(b) shows the estimated fatigue to reach the successive target locations. Fig. 9(c) and 9(d) depict corresponding mean speed and RMS error to reach the target locations. Overall, fatigue is high if velocity or error is high. The intelligent system autonomously applies resistance or assistance to match patient performance and stops the exercise when fatigue reaches its maximum limit, which is set to 10 in this example. The main motivation of the automated system is that a therapist needs not to be always present with a patient; rather an intelligent system can guide the patient through simple reaching exercises and this may help to extend rehabilitation to a remote location. Our future work will improve the intelligent system in that...
target locations and time constraints can also be set by the intelligent controller.

**F. Video games**

The GUI also includes video games to encourage the patient to perform repetitive motion exercises. Fig. 10(a) shows an example of a game called, Bouncing Ball. The patient controls a bat position with the robot end-effector to prevent a bouncing ball from hitting the ground. There are several parameters that can be varied to change the difficulty level of the game. The speed of the ball and haptic effect (resistance or assistance) can be changed to improve control accuracy and muscle activity. The game GUI provides scores, which show the numbers of balls returned and missed, as feedback to the patient and therapist. This game also includes an AI system that automatically changes ball speed and haptic effect to match user performance.

Fig. 10(b) shows another example which is a strategic type of game. The game GUI includes some objects common to a living room. The objects are initially placed randomly in the environment. The patient can control a cursor with the end-effector to select and reposition an object in the environment. The overall goal of the game is to rearrange all the objects so that the environment looks like a familiar living room environment. It is believed that the tasks of selection and repositioning of an object will increase a patient’s control accuracy. This game also includes different haptic effects. For example, the patient will feel resistance while going through an object or the boundary. It can apply different resistance levels to different objects. The system can also apply assistance to help the patient to reach a particular object position in the environment.

Fig. 10(c) shows a car driving game. The main goal of the game is to control the speed and position of the car to avoid collisions with the obstacles placed on the road. The forward motion of the end-effector controls the speed of the car and sideways movement controls left/right position of the car. The game GUI provides several options to change the difficulty level of the game. For example, the obstacle size and position can be randomly changed to improve control accuracy. Different haptic effects can also be included to improve muscle activity. For example, the game GUI provides options for applying road resistance and collision effects. This GUI also provides scores so that the patient is encouraged to play the game for longer duration.

**IV. THERAPIST FEEDBACK**

A group of stroke therapists was consulted to get their feedback on the features of the robotic prototype. The purpose of the focus group was to refine the features, specifications, and user interfaces of the developed robotic device.

**A. Methods**

The participants included therapists (physiotherapists and occupational therapists) from a local rehabilitation hospital and members from the design team, and the moderator for the sessions was a professional moderator. Therapists included in the study had to have at least two years of experience working in upper limb rehabilitation with stroke patients.

The session was 80 minutes and conducted in three steps: 1) general discussion on the current state of upper limb stroke rehabilitation technology; 2) description of and interaction with the developed robotic system; and 3) feedback on the system. This section will mainly focus on the feedback step. Most of the therapists tested the robot with and without haptic effect (force feedback). The haptic effect was set to provide maximum 10N of force feedback to ensure safety of the users.

**B. Results**

Seven therapists participated in the focus group. There were three physiotherapists and four occupational therapists. All had Master’s degrees in their fields. Four had 2-5 years of experience in stroke therapy, two had 6-10 years of experience, and one had more than 10 years of experience. They had all treated populations of adults (18-64 years old) and older adults (65 years old and over). One had experience in treating youth (11-18 years old). They had experience working in a rehab hospital setting, with two in acute care settings. In addition, two had worked in long-term care, three had worked in outpatient clinics, two had worked in home care, and one had worked in a home-based private practice. The following sections briefly describe their feedback on the robotic device and GUI for stroke therapy.

**C. Robotic device**

**System size & safety:** Most therapists felt that the device was too heavy and large for home use. They found that the device is unsafe for clients to use alone, because of visible electrical wiring, but predominantly because patients may not have sufficient trunk support. The device would need to have more rounded edges to prevent injury. They also suggested a longer forearm support end-effector for user safety.

**Degree of freedom:** The current system can mimic only planar types of exercise, which was felt to be insufficient. Therapists would ideally like to see a 3DOF system, however, considering cost trade-offs of a 3DOF system and haptics, they opted for haptics.

**Range of motion:** Most of the therapists felt that the full range of motion (ROM) of the robot workspace is not adequate for different planar exercises. One therapist, however, mentioned that this could be solved by repositioning the patient’s seat position for a different exercise.

**Monitoring postural compensation:** All felt that the robotic system needed to be equipped with additional sensors...
to detect compensatory postural movement while performing the exercises with the robot.

**Haptic effect/Force feedback**: Some therapists felt that the main feature of the device was adequate force feedback in terms of resistance. The therapists, however, also mentioned that they would prefer assistance over resistance in a haptic rehabilitation device. The therapists also expected that the robotic device would measure the force applied by a patient on the robot end-effector, which is not available in the current system.

**Biofeedback**: Biofeedback was seen as a desired feature by some therapists to allow therapists and their patients to have information relating to joint position, muscle use and activation. The current system, however, does not provide any biofeedback.

**Cost**: The therapists suggested that the device cost should not exceed $5000 for clinical use. One of the therapists also suggested that she could recommend her patients using this device for home use on a rental basis for $50 a month.

**D. GUI**

The therapists did not have a long time given time restrictions for the focus group to test the exercise modes and video games. As a result, individual feedback sessions are being arranged to evaluate the GUI with the same therapists who participated in the focus group study. The following sections include some of the feedback from the focus group and from two individual sessions.

**Haptic interface**: Most of the therapists felt that the current haptic interface is satisfactory to control resistance and assistance. They also emphasized adding more real world objects for resistance control. It was also discussed that the force applied for assistance should be moderate enough so that the patients can keep up with the end-effector motion.

**Performance analysis**: The therapists felt that the numerical performance data shown in the GUI was not good enough feedback, as sometimes these numbers were not intuitive. They also expected data feedback in report format, e.g. current ROM of the patient, which can be printed for further analysis. Some of them suggested having a randomized three minute video recording with timeline information to understand how the patient was using the device.

**Exercise**: The therapists seemed to be interested in the different modes of exercises provided with the GUI. Some of them argued that the fixed planar exercise is usually applied for the first stage recovery of post-stroke patients. The other stages require the exercise plane to be oriented at different angles. The developed robotic device, however, can be positioned either vertically or laterally and thus it provides only two planes of exercise. Overall, they think the exercise will be convincing if it can be shown to improve recovery of stroke patients.

**Video games**: Most of the therapists felt that video games would be an important part to a rehabilitation robotic system. They mentioned that the games provided with the GUI were visually motivating and would help their patients be more compliant with exercise programs. Some of them also mentioned that the games could be cognitively challenging for their patients. Cognitively challenging games, however, could have both positive or negative effects depending on the patient’s needs. Some of the games may require a certain degree of cognitive ability, and thus restricting some patients from using them. Alternatively some therapists may like to incorporate some cognitive exercise in the games so that they are stimulating cognitive skills as well as motor recovery. Our project consultant therapist, Dr. Debbie Hébert commented that different games could have different activities for different treatments. For example, clients with apraxia could use activities that require sequencing in 'real life' tasks - like dressing, making a meal, etc.; clients with attention problems could use activities that require scanning - like the driving game.

**Human robot interaction**: The therapists mentioned that the current system lacks the human robot interaction feature. They suggested modeling a virtual therapist/coach avatar using the picture or voice of a therapist to guide and encourage a patient throughout the therapy. An avatar could also be a part of the postural compensation monitoring system to alert patients if their body positions deviated from the prescribed program.

**E. Discussion**

The current system is at a developmental stage and therapist feedback shows an overall conceptual acceptance of the developed system. There exist several scopes of improvement required for the robotic device and GUI. It should be noted that none of the therapists had prior experience with rehabilitation robotics and it may have been hard for them to discuss the device without having a reference with which to compare. In addition, they had limited time to try the prototype during the focus group. Not having this reference and not testing all the features of the robot themselves, may limit the extent to which they can give detailed feedback on the current prototype. Nevertheless, these therapists have experience in neurorehabilitation and in working directly with stroke survivors, so their feedback is valuable to help guide design.

Therapists who do not have experience with robotic rehabilitation may have a certain standard in mind before being open to using robotic therapy with their patients. To overcome this problem, as one therapist suggested, clinics could be set up with robotic devices which would allow therapists to experience using the device.

Overall, the therapists seemed enthusiastic about developing a RRD. Many felt that one of the advantages of the prototype was that it could help those with more physical impairment, as there is a lack of treatment options to aid these individuals. The therapists saw the potential in the project and would like to participate further and see the clinical trials.

**V. Future Work**

The focus group study shows that the current system can be improved in many ways. Our future work will be directed
towards fulfilling the therapists’ suggestions and conducting more studies with therapists and stroke survivors to further improve the design. Hence, we define the following future goals to be achieved.

A. Robotic system

The device needs to be improved in safety, workspace, portability, and usability. We note that the device also requires a better method of securing it to a table. The end-effector should be better designed to support and secure the paretic hand.

B. GUI

The haptic interface needs to be improved by adding more real-world resistance levels realizable by the patients and therapists. The assistance force levels also need to be tuned with respect to the therapist’s visual perception capability. In case of poor visual perceptual skills, the system needs to incorporate audio feedback for assisting the therapists. The GUI also needs to provide exercise data in useful report format for further analysis. It should include different games with different activities to match requirements of different patients. Finally, it should incorporate a virtual therapist/coach avatar to encourage the patient throughout the therapy.

C. Ongoing and future studies

A study that is currently in progress involves individual therapist trials of the GUI and VR games to gain feedback to improve the therapist and stroke survivor interfaces, explore how therapists think a RRD can be integrated into clinical practice and better define the clients who might benefit from robotic therapy. Feedback from patients is equally important and recruitment is underway for a stroke survivor focus group to evaluate the RRD. Additionally, a clinic for upper limb rehabilitation is planned so that therapists and their patients will have the opportunity in the future to work with improved versions of the RRD in a cutting-edge treatment development and evaluation clinic setting.

VI. CONCLUSION

This work presents preliminary developments of a portable rehabilitation robot for upper limb post-stroke patients. The robot also provides haptic feedback for targeted treatment of the paretic upper limb. The system also provides a GUI that includes both supervised and automated reaching exercises using the developed robotic device. The GUI also includes video games to motivate the stroke survivors to be engaged in the movement training.

This work has also included a focus group study where experienced therapists expressed their views on the developed system. The therapists were enthusiastic about the developed robotic system; however they felt that there were many scopes for improvements.

Our future work will address the therapists’ feedback to make this portable upper limb RRD a step towards the development of an appropriate tool for therapists to use in stroke therapy.

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