Development of CR2-Haptic: A compact and portable rehabilitation robot for wrist and forearm training

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Abstract— **Stroke has now become the leading cause of severe disability. Rehabilitation robots are gradually becoming popular for stroke rehabilitation to improve motor recovery, as robotic technology can assist, enhance, and further quantify rehabilitation training for stroke patients. However, most of the available rehabilitation robots are complex and involve multiple degrees-of-freedom (DOFs) causing it to be very expensive and huge in size. Rehabilitation robots should be useful but also need to be affordable and portable enabling more patients to afford and train independently at home. This paper presents a development of an affordable, portable and compact rehabilitation robot that implements different rehabilitation strategies for stroke patient to train forearm and wrist movement in an enhanced virtual reality environment with haptic feedback.**

I. Introduction

Cerebrovascular accident or stroke is the leading cause of severe disability worldwide, with up to 15 million people every year. Fortunately, rehabilitation can help stroke patients to regain their functional movement. However, conventional rehabilitations generally involves one-on-one interaction with physiotherapists who assists and encourages the patient through repetitive exercises are labor intensive, expensive and lack of objective assessment as well as quantitative diagnosis and evaluation [1]. This led to the shortage of physiotherapists due to large number of patients. Rehabilitation robots are proven to help and improve stroke rehabilitation [2], as robot-assisted therapy able to provide consistent and intensive treatment important for efficient functional movement recovery [3]. Rehabilitation robot also promotes motivation through strategy games and virtual reality technology as well as train width range of exercises.

However, most of the rehabilitation robots such as ARMin [4] and Gentle/s [5] are complex and involve multiple degrees-of-freedom (DOFs) causing it to be very expensive. Rehabilitation robots needed to be useful but also should be cost-effective to be able to apply in current rehabilitation process [6]. It needed to be at a suitable cost range so that more patients can afford them and train independently at home. Generally, the higher the complexity of the design, the higher the cost and more supervision is needed, prompt the number of potential users to reduce [7].

For more complex robotic system, which allow training for usual functional tasks involving the hand function in principle, requiring technical assistance and making the system unsuited for decentralized use at hospital, rehabilitation centers or homes [7]. It would be beneficial if the complexity of the robot design could be simplified while performing the essential training for activity daily living. Thus, this project proposed an affordable, compact and portable rehabilitation robot that is used to train the movement of forearm and wrist which require less preparation effort and easy to be set up.

II. System Requirement

The system requirements are designed based on the previous studies [6–8] as well as the feedback of the therapists and patients from rehabilitation centres and hospitals through interview. In term of portability, the robotic system need to be light weight and small enough to be able to fit into a typical car and carried by one person. The design is required to be compact enabling multiple functional training movement to be integrated into a single device within limited space. The motivational elements are needed to encourage patient engagement, for example virtual reality games and objective assessment for progress review.

To summarize, the robotic device needed to be suitable for decentralized usage, motivational, easy to set up, portable, affordable and compact as listed in that Table I.

TABLE I. System Requirement

Features	Description
Portable	Fit into car and carry by one person
Compact	Able to train for multiple functional movement in limited space
Motivation	Provide virtual reality game and objective assessment
Suitable for home use	User friendly and easy to set-up

Forearm and wrist training are targeted in this project is because these two are the important movements for human activities daily living [9]. The range of movement and

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stiffness for each joint is identified and listed in Table II [10], [11], before the robot development. Due to the cost constraint, the joint stiffness is important to be known in order to select the suitable actuator which is sufficient enough to rotate the forearm and wrist in pure flexion-extension (FE), radial-ulnar deviation (RUD) and pronation-supination (PS).

TABLE II. WRIST AND FOREARM PROPERTIES

Joint		Range of movement (degree)	Passive joint stiffness (Nm/rad)
Forearm	Supination	86’	0.19
	Pronation	71’	0.24
Wrist	Flexion	73’	0.55
	Extension	71’	1.02
	Radial deviation	33’	1.71
	Ulnar deviation	19’	1.25

The functional rehabilitation training is aims at exercising activities that do not require high torque, such as activities of opening or closing a jar which require about 0.7Nm [12].

III. ROBOT DESCRIPTION

A. Design

Fig. 1 show the developed robotic system; CR2-Haptic, which is an one degree-of-freedom (DOF) rehabilitation robot that can be used to train wrist and forearm movement. The robot enables the patient to train their muscle function while playing the virtual reality games provided in the display.

Figure 1. CR2-Haptic robot with healthy subject

To fully utilize the single DOF of the robot, the robot was designed compact which is able to use in training of multiple wrist, forearm movement as well as basic activities daily living (ADLs) as shown in Fig. 2 and 3. By changing the orientation and the suitable modules of the robot, the robot can be used for multiple training movement to fit the need of different setup in conventional rehabilitation training in a limited working space. To prevent daily use of the device from becoming a burden for the patient and therapists, the set up procedure was designed to be as simple as possible, which take about 2 to 3mins for the patient to train in every training session.

Figure 2. Typical forearm and wrist training set-up. (a) Pronation and supination, (b) Dorsi-flexion and palmar flexion, and (c) Radial and ulnar flexion

Figure 3. Functional activities set-up. (a) Turning door knob (b) Turining key slot (c) Opening or closing jar.

B. System Overview

The system overview was shown in Fig. 4. Impedance control was applied in this system where the input units are the current sensor, rotary encoder and pulse oximeter (CMS-P). The current sensor and rotary encoder are used to measure the torque input of the subject and position feedback for the robot. These data are sent to Tiva™ C Series LaunchPad and then to the central processing unit, which is a laptop through USB communication for data processing. The pulse oximeter, which is used to obtain the heart rate of patient, is connected directly to the laptop through USB.

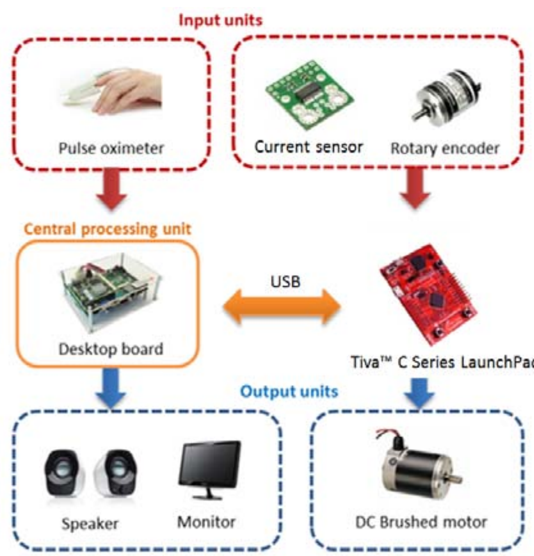


Figure 4. System overview of the robot

The haptic rendering is achieved by giving the output command to change the speed of the motor for haptic sensation. The visual and audio outputs by the desktop board are used to match with the haptic forces applied by the robot for a realistic sensation of virtual environment. The time, position and torque of the movement were measured to provide objective assessment for the performance review of the patient after training.

C. Specification

The robot has a maximum rotation range of movement of the robot is +/-135 degree and generated torque of 1.8Nm, which is sufficient to train for wrist and forearm movement. The robot was designed to be low impedance (backdrivable), at which the patient able to freely and the effective friction, inertia, and stiffness are low enough for the patient to feel as if no robot was connected. The rotational inertia is at 0.325kgcm^2 which is within the acceptable range for backdriveability of the device [13]. This key aspect is important to avoid excessively interfering with the patient's natural arm dynamics. To summarize the robot specification are listed in Table III.

TABLE III. ROBOT SPECIFICATION

Specification	Value
Maximum rotation of interface	+/- 135 degree
Maximum generated torque	1.8 Nm
Friction torque for rotation	0.02 Nm
Rotational inertia	0.325 kgcm^2
Rated speed	3200 rpm

D. Safety

Safety was the main issue for human-machine interaction. Therefore, to prevent any harm or unexpected runtime error, various safety were implemented. The safety features include no sharp edges in any mechanical parts and mechanical ends stop to guarantee that no joint can exceed the anatomical range of motion. Redundant electrical fuse was apply in the main circuit to provide overcurrent, mis-matched load, short-circuit protection. An emergency stop button was installed at the top of the robot, so that it can be used to cease the operation during any emergency situation by the therapist or patient. Current and speed monitoring are implemented in the software to monitor the status of the robot during the training. Since the device is backdrivable , the robot can be easily moved manually when it is non-powered in order to release the patient from any potentially dangerous or uncomfortable posture. Last but not least, the pulse oximeter was used to monitor the patient heart-rate to avoid from over-exhausted during the training.

IV. IMPLEMENTATION AND PERFORMANCE

Three control modes were developed and implemented into the robot, which are passive, assistive and active modes to suit for different stages of rehabilitation training. The performances of the control modes were then analyzed.

A. Passive mode

In passive mode, also known as Continuous Passive Motion (CPM) mode is used to guide the patient who cannot move their arm. Proprioception rehabilitation training strategies was integrated by having the hot air balloon to illustrate the movement of the joint in virtual reality environment. The purpose of proprioceptive rehabilitation is to retrain altered afferent pathways to enhance the sensation of joint movement and this is highly recommended to promote dynamic joint and functional stability [14]. Fig. 5 (a) shows the implantation of proprioception rehabilitation training in the robotic devices. The hot air balloon in the virtual reality will fly in a sinusoidal pattern while patient's hand is moved passively by the robot. Fig. 5(b) show the actual and desired position of the implementation with a flaccid sub-acute stroke patient. For safety purpose, the motor output was set within a moderate range to avoid any harm to patient, therefore the actual position do not achieved the end of the desired position which is the position with high muscle stiffness at the end of the joint.

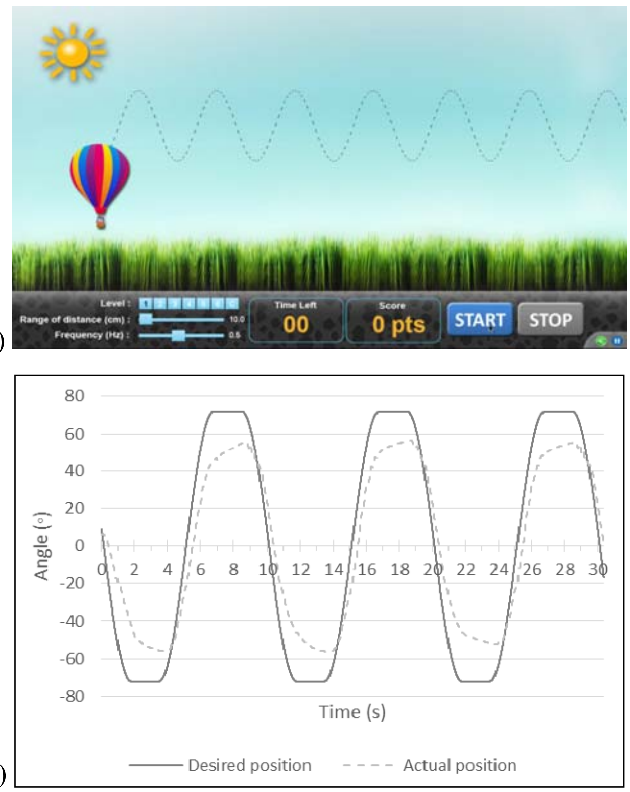
(a)
(b)


Figure 5. (a) Software interface of training therapy. (Left) Flying Balloon; a passive mode training game and (b) Output response with stroke patients

B. Assistive mode

In assitive mode, the robot provide impedance-based assistance by implementing the assist-as-needed algorithm. In assitive mode, if the patient cannot move within a set time period, the robot will assist them to complete the movement by achieving the set target in the game. The game requried the patient to collect the water drop from the sky. If the patient is able to move in full range of movement actively to collect the water drop and achieve target three time continuosly, the training will proceed to the next level with active mode for resistance training.

C. *Active mode*

In active mode, the robot will exert different level of resistance to strengthen the muscle strength of the patients by adjusting the speed of the motor depends on the recovery rate of patient. Haptic simulation was used for resistive training in the active mode. The advantages of this approach over training in physical reality are it can create many different interactive environments making it more interesting, realistic and flexible than typical rehabilitation clinic [15], [16]. The effect of pendulum [17] was simulated by applying the mathematical model as shown in Fig. 6 in active mode training. Torque, t is the generated resistance that simulate the pendulum effect for the user through robotic device.

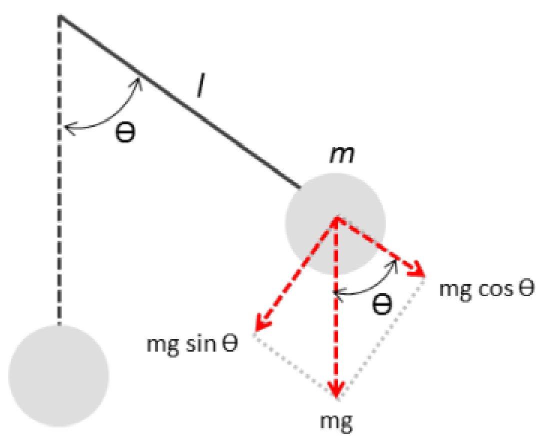


Figure 6. Mathematical model of pendulum haptic simulation in resistive training therapy

$$\text{Torque, } t = mgl \sin \theta \qquad (1)$$

where m is the virtual mass, g is the gravity constant, l is length of the pendulum. Torque, t will be higher if the mass, length of level and θ increase. Fig. 7 shows the interface of the SkyDrop that apply pendulum haptic simulation for resistive training. Pronation and supination movement will move the cup to left and right. The greater the distance of the cup with the central at 0’ the higher the resistance will exert to the user. The pronation and supination training range of movement is set from -80’ to 80’.

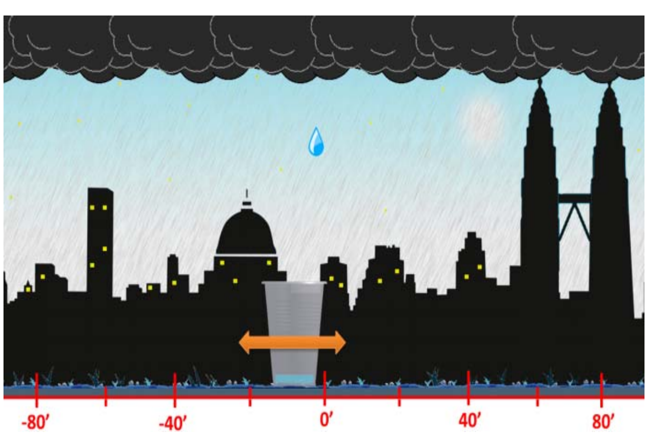


Figure 7. Software interface of SkyDrop game

Fig. 8 shows the torque distribution across the movement from -80 to 80’in different level of difficulty measured by using a digital torque gauge (MARK-10 Series 5i). The average minimum (Level 1) and maximum (Level 5) torque measurement is 0.14Nm and 0.74Nm. This is a progressive resistance training in which the higher the level the greater the resistance applied.

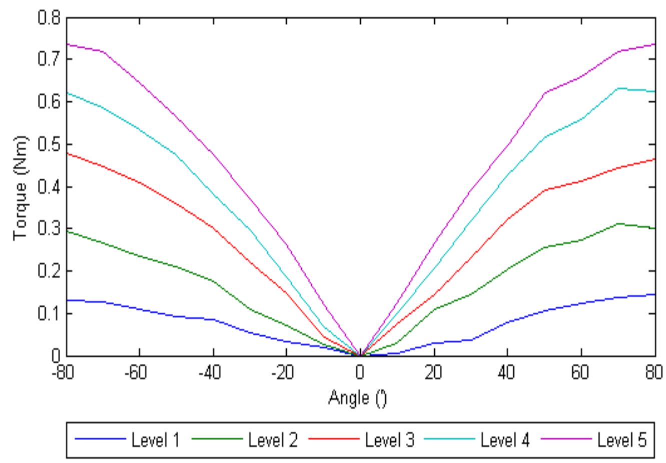


Figure 8. Torque distribution for different level of difficulty

Customized software was developed to simulate the magnet effect for resistance training. The purpose is to provide another realistic sensation to increase the training interaction. The red and blue color indicates the north and south polarity of the virtual magnet. The torque of the simulated magnet sensation was analyzed. Fig.9 and Fig. 10 show the analysis set up interface for same and different polarity of two virtual magnets. By setting the same polarity for the two virtual magnet, the torque measurement started from 90’ to -90’ with 10’ increment for three trials. The torque with shorter level of the virtual magnet was measured to indicate the different torque distribution. The same procedure was repeated for different polarity of the virtual magnets.

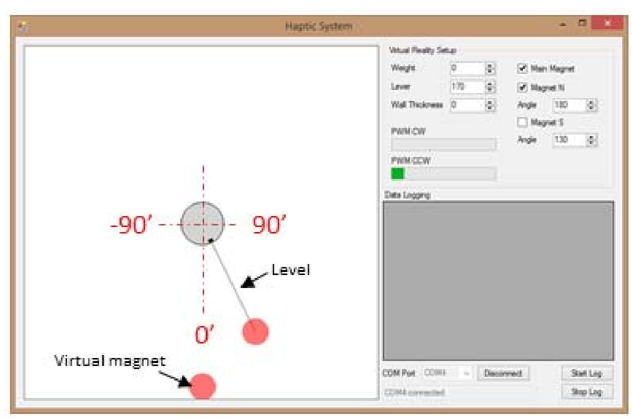


Figure 9. Haptic-Demo software for same polarity

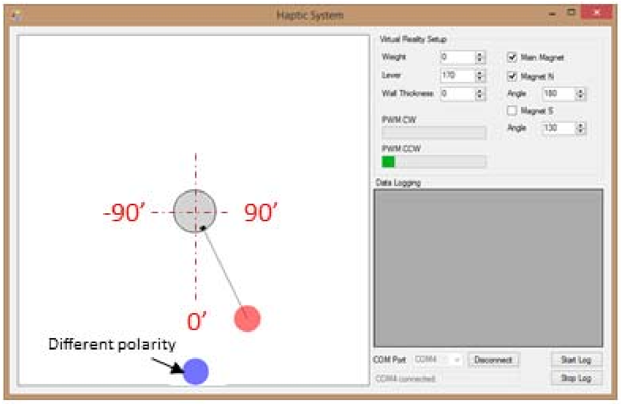


Figure 10. Haptic-Demo software for different polarity

Fig. 11 and Fig.12 shows that the torque distribution of the magnet simulation from 90' to -90'with different polarities. The maximum torque for same polarity of the virtual magnet was 0.495 Nm and the maximum torque in same polarity was 0.563Nm.

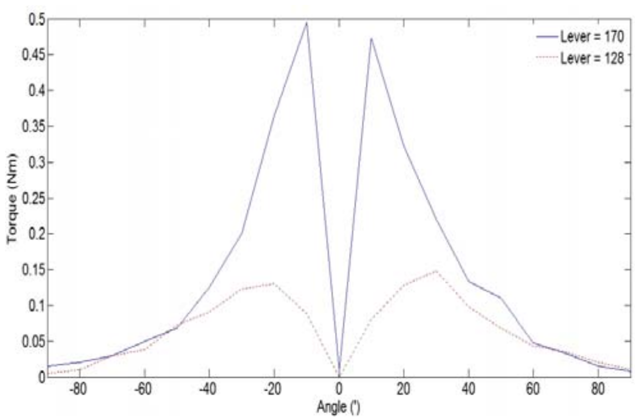


Figure 11. Torque analysis for same polarity

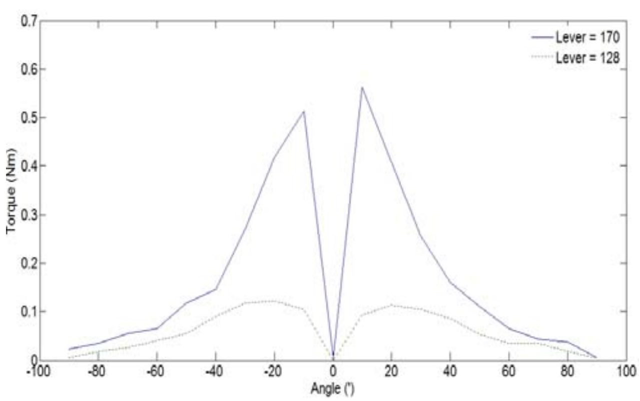


Figure 12. Torque analysis for different polarity.

V. Results and Discussion

This paper presents a development of a portable and compact rehabilitation robot for wrist and forearm stroke rehabilitation. The developed training modes were integrated with different rehabilitation strategies; proprioceptive and haptic simulation with pendulum and magnet rendering for resistive training. These training modes may potentially improve motor function as well as cognitive recovery, due to different stimulus modalities and levels of complexity in virtual reality games enable persons with stroke to train their cognitive skill during rehabilitation [18]. To validate the effectiveness of the developed robotic system strategies, further clinical study will be conducted.

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