Virtual Rehabilitation Robot-Preliminary Thoughts

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Abstract—**Robotic rehabilitation is a promising approach to rehabilitation of post stroke impairments. For that reason, a robotic arm will be used for the upper-limb rehabilitation of stroke patients. This project is to study, analyze, design and implement a wirelessly communication manipulator with three degrees of freedom. The manipulator has a possibility to operate in different planes, allowing patients to perform rehabilitation exercises while playing video games. These games are based upon the rehabilitation protocol. They must be designed carefully for the exercises taking into account the patient's age, strength, mental condition and the affected locations of the brain. The final step will be testing the device at different planes (horizontal, vertical and inclined). The test must be done with real cases under a direct supervision of a specialist in physiotherapy. The results are essential to study the planes suitability for rehabilitation (especially the inclined plane) and the overall enhancement in the patient's condition.**

Keywords- Robotic; Rehabilitation; Post stroke; Upper limb; Wirelessly-operated mechanism; Video games.

I. INTRODUCTION

Impairments could happen due to trauma, stroke or brain injury, cerebral palsy, incomplete spinal cord injuries, multiple sclerosis. Other impairments could affect the musculoskeletal system such as bone fractures, muscular dystrophies, limb's burns or even a cut in the muscles or blood vessels [1]. According to World Health Organization (WHO) cerebrovascular accident (CVA) is the second most common cause of death in high and middle income countries and the sixth in low income countries. In 2008 for example about 6.15 million CVA patients died [2]. In Hebron, the number of CVA patients increased to 540 cases with a 139 new cases in just a year (04/08/2009 - 04/08/2010) [3].

In general, rehabilitation aims to help patients to restore, develop or maintain physical, psychosocial, cognitive and/or communication skills according to the type of impairments. While cognitive and communication skills are not important for some types of impairments that have a direct or physical effect on the affected limb such as bone fractures, burns…etc. They must be taken into account as in the case of CVA when the affected limb is the brain. Impairments need rehabilitations immediately after receiving the appropriate clinical treatment. The rehabilitation techniques and exercises differ and they are not the same for all impairments, they depend on the type of impairment, location and age of the patient.

Virtual rehabilitation is the use of virtual reality (VR) and virtual environments (VE) within rehabilitation. VR and VE can be described as a simulation of real world environments through a computer and experienced through a "human-machine interface" [4]. The importance of virtual rehabilitation arises due to the lack of motivation in the traditional rehabilitation with physiotherapy. The patient feels bored as a direct result of monotony and repetition in traditional therapeutic exercises. However, in order to get the motivation and enhance the rehabilitation process, an interesting computer game should be placed in front of the patient [5] and [6].

This paper presents preliminary thoughts about a virtual rehabilitation robot. It is consists of seven sections. Section II presents the need for such a robot in the rehabilitation processes. Section III describes an overview for the robot parts, and there functional specifications. Section IV listed the required sensors and actuators. Section V presents an overview for the communication wireless modules which will be used for connecting the robot side with the computer side. Section VI describes the computer and software part including (games design, levels description, and mapping between the workspace and the screen). Section VII presents the conclusion and the future work.

II. RECOGNITION OF THE NEED

From preliminary discussions with several occupational and physical therapists like Dr. Akram Amro [3], Dr. Ali Abu-Ghazala [7], Samih Dweik [1] and Munther Oweiwi [8], it has been concluded that there is a need for active-repetitive exercises under the therapists' supervision without the necessity of his direct intervention during exercises. However, therapists face a problem in motivating patients who get bored quickly.

Patients' motivation is achieved by linking rehabilitation exercises to well-designed computer games. This could be done by letting the interaction with the game to be through an active manipulation of a specially-designed mechanism. In rehabilitation exercises, there are other things which are crucial to complete the exercise correctly rather than moving a weak limb without any resistance in the space. For example, strengthening the affected muscles to restore the normal strength or just below the normal of a healthy person with the same age. After that, the patient should be able to withstand with normal resistance or loads that the person could face in daily life activity. The specially-designed mechanism is needed for strengthening the muscles rather than motivating the patient. Otherwise the patient could use a computer mouse or a small piece without the need for such a mechanism.

Usually the patient is asked to move small objects with different masses from one place to another. These objects are not always available with a large range that is suitable for all patients. In addition, the occupied volume of these objects in the clinic is large which could be annoying for both the therapist and the patient.

As a result, the required device must allow the interaction between the patient and the virtual environment (game), with a wide range of virtual weights. In addition, a record for the patient's progress during the session is preferred.

As the device introduces a new technology for rehabilitation in Palestine, it should satisfy some features and requirements. According to physiotherapy specialist Dr. Akram Amro [3], a stroke rehabilitation device must allow the following features: 1) Eye-hand coordination, 2) Combined movements (functional movements), 3) Certain amount of resistance to increase the muscle strength, 4) Completion of visual tasks, 5) Passive movements for some cases, 6) Plane motion (horizontal plane for example to draw circles or squares) is suitable and useful. However, it is preferable to allow for three dimensional motions.

There are other requirements such as: 1) The device must be safe for both patient and therapist, 2) The device including the game must be suitable for patients of different ages, 3) The device must be convenient for patients with different sizes, 4) It must be suitable for both body sides, 5) Flexibility in the device is required. For example, if the patient is sitting rather than lying in the bed or sitting on a chair, he/she should be able to use the device [7] [8].

III. Conceptual Design and Functional Specification

Before building any device, a set of parameters must be considered, they are divided into two groups. The first one is related to device itself such as: 1) safety, 2) portability, 3) cost, 4) friction, 5) design simplicity, 6) workspace availability, 7) volume occupied by the device, 8) ability to afford heavyweights (also known as mechanical stiffness) 9) needing special components such as an adjustable table or chair. The second one is related to the patient such as: 1) size, 2) suitability for both hands if the patient suffers from left or right hand impairment.

For that, it is desired to design and produce an electro-mechanical device with measurement sensors that use computer game as an interaction tool. The device will be designed on the basis of the mechanical movement of the arm. The process starts when the patient holds the end-effector of the mechanical device with his/her arm. As the patient moves it in the workspace, sensors detect this motion and translate the change in position into electrical signals. These sensors are connected to a microcontroller called Arduino which in turn will send the signals to a ZigBee module. ZigBee a special module that allows signals to be transmitted and received wirelessly. The computer can now deal with signals as they represent the position coordination in the game that is displayed on the screen. The game could be moving things for example in which the patient is asked to move an object from one place to another. This movement should happened with the feeling of the actual weight of the object. To achieve this, the device through rotary dampers will resist the patient in his/her arm movement. The patient will perform an extra effort to move his/her arm while moving the object only. With different changing in resistance, the patient will feel that the objects are of different weights or materials. The block diagram of the whole system is shown in Figure 1.

The device is divided into systems, these are: 1) Mechanical device system, 2) Load system, 3) Sensors and interfacing system, 4) Computer and software system.

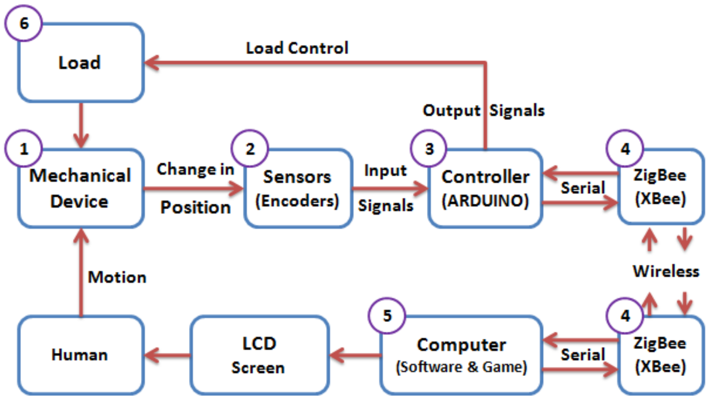

Figure 1: Block diagram for the whole system

A. *Mechanical device (block 1)*

The design is based on a parallelogram linkage. The main features of this arrangement are: good rigidity of the structure, direct drive of the manipulandum, which eliminates any backlash in the force/motion transmission and minimization the overall inertia, because most of the mass is either fixed, or close to the rotation axes [9]. The parallelogram manipulator choice is based on an open source design called Braccio di Ferro [9]. This design has two degrees of freedom either in vertical or horizontal plane. The project team will add a new degree of freedom called the configuration angle, and study its enhancement on the patient's condition. However, the device with its three degrees of freedom will allow working in inclined planes in addition to vertical and horizontal planes.

This system consists of the mechanical arm with the attached components and the frame of the device as shown in Figure 2.

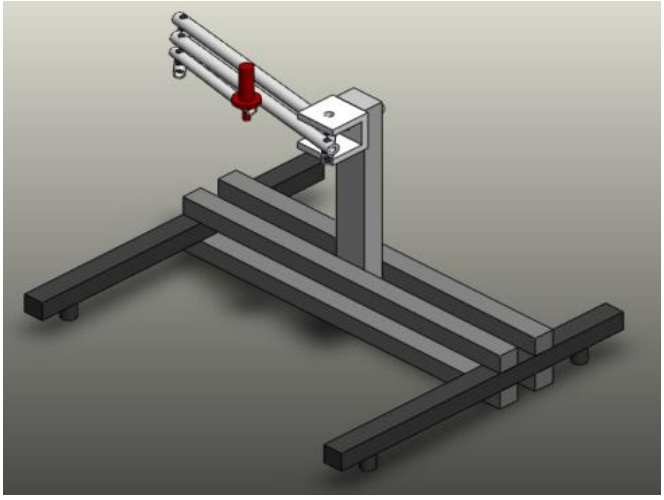

Figure 2: The mechanical arm with the frame only at the initial position

Figure 3 shows the top view of the manipulator. The manipulator must satisfy some requirements like mechanical rigidity (which is the ability to withstand with the load that result in this case from the patient). The design should compromise between the mechanical rigidity and the device weight. The suitable workspace for the patients is an elliptical shape with 800 mm × 400 mm [9], which is shown also in Figure 3. This workspace can be achieved using a manipulator with two degrees of freedom. Appendix A describes the coordinates of the end-effector in the robot coordinate system as a function of the joints' angles. The device must be back-drivable with low inertia and friction for the patients to get started with. The friction will be controlled to simulate the increasing load.

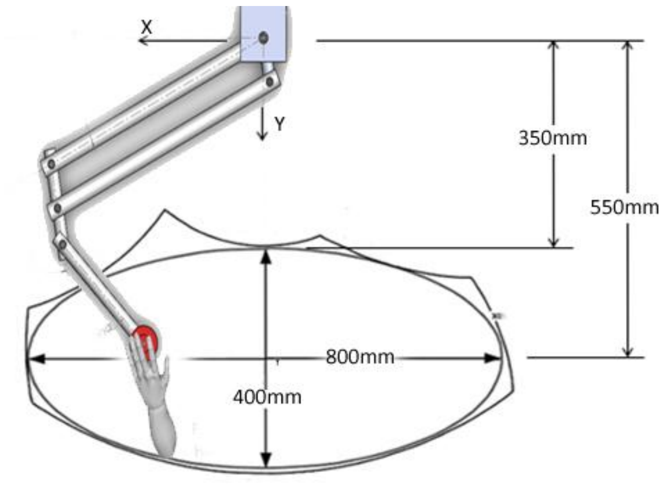

Figure 3: The workspace and the mechanical arm in two dimensions [9]

The mechanical arm will be built using Aluminum. It will be connected to the iron frame by a revolute joint which adds a new degree of freedom. This new degree of freedom will provide therapists with three configurations (horizontal, vertical and inclined in any desired angle) for the same device. Which could be useful for training different set of muscles with different exercises' levels in the rehabilitation session. In addition, a change in configuration angle causes gravity effects.

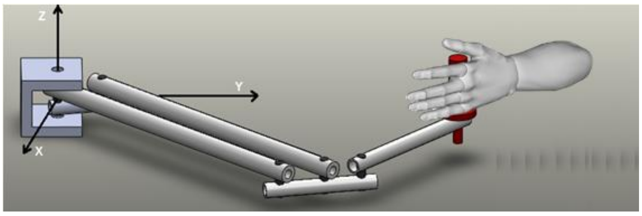

Figure 4: Left view of the manipulator in the horizontal plane (XY)

B. Load system (block 6)

The load is used to stop or reduce the motion of an object which is necessary in virtual environment to simulate the interaction of the patient with the virtual object. As the patient progresses in the game, he/she should be able to interact with different weights of objects. To achieve that, a resistance control is required without annoying the patient or affecting the virtual environment.

Rotary dampers are preferable for this type of device with revolute joints, but these dampers must have some requirements that are necessary such as an adjustable damping ratio and a bidirectional damping effect.

Dampers with adjustable damping ratio are called semi-active dampers which produce only a modulation of the damping forces in the controlled system according to the control strategy employed [10]. Thus the amount of damping can be tuned in real time.

Controlling dampers can be achieved by a command from the computer, but this command must be send wirelessly using ZigBee to Arduino, which in turn will produce the required controlling signal.

C. Sensors and interfacing system (blocks 2, 3, 4)

As the patient holds the end-effector of the mechanical device with his/her arm, the motion that results in the workspace is detected using motion sensors. These sensors translate the change in position into digital electrical signals.

The chosen motion sensors must afford a high resolution for determining the accurate position and the selected configuration. The sensors will be connected to the Arduino which allows receiving the input signals (sensors) and controlling the output signals (dampers).

One of the requirements of the device is portability. To achieve that, a greater movement freedom can be reached using wireless communication through a technology that covers larger area and allows for obstacles avoidance which could exist in the therapy session. Those requirements can be satisfied using a special module called ZigBee with two hardware parts which allow signals to be transmitted and received wirelessly. The first part will be connected to the Arduino and the other part will be connected directly to the computer. Each part is capable to transmit and receive data at the same time.

D. *Computer and software system (blocks 5)*

A computer is required to have a real time load control (dampers), interesting games with different levels, a record for the patient's progress during the session and synchronization between the patient's motion and the game.

The game requirements are achieved through a solid software such as C# which is a programming language that is simple, modern, general-purpose, strong type checking and object-oriented programming language, it was developed by Microsoft [11]. The other requirements depend on the computer specifications.

The data is received from the ZigBee module to locate the position of the end-effector on the screen and determine the used configuration that will be used to choose the suitable game. During the game, the computer must control the level of the game, record the patient's progress during the session and control the load.

IV. Sensors and Actuators

The motion of the mechanism in the workspace is detected using sensors. Three sensors will be used (two for the position) and the third for the configuration, these sensors translate the change in position into digital electrical signals. While the patient is progressing in the game, he/she should be able to interact with different objects' resistances, in order to achieve that, loads control is required.

A. *Encoders*

Sensors are needed to find the exact position of the patient's hand. Because the patient always holds the end-effector during the exercise, finding the end-effector position will give the patient's hand position. The end-effector position can be determined using three angles two of them correspond to the position in the plane. The third angle determines the chosen configuration. To measure these angles, rotary encoders are needed.

The specifications of the encoder must satisfy some requirements to complete the task with a minimum cost. The inertia of the encoder must be small and the frequency response must be high enough to maintain a good accuracy for the device.

Using an incremental encoder means that the initial position of the manipulator is unknown. To solve this problem an initial position of the manipulator with known values of the angles as shown in Figure 2 can be used.

B. *Dampers*

Dampers are passive components that depend on the speed of the affected force or torque. If the speed is small the damping force/torque is small and vice versa. These components are preferred in rehabilitation devices for safety reasons.

In contrast to active control devices, semi-active control devices cannot inject mechanical energy into the controlled system and, therefore, they do not have the potential to destabilize it. Examples of such devices are variable orifice dampers, controllable friction devices and dampers with controllable fluids (e.g., electro-rheological and magneto-rheological fluids) [10].

Ideas for implementing the damper include MR fluid. This method has many advantages like the speed response and the small size but it is available for linear damper only. An idea to construct one is by using rotary disc-type MRF dampers. A final choice will be using a small motor to control a normal rotary bidirectional damper.

V. Communication System

One of the most important features is the flexibility of the device. To achieve that, wireless communication will be used. Thus adds a greater movement freedom. By this way, the rehabilitation device can be used easily while patient is sitting or standing with the ability to move and transfer the device to different places in the room. This is achieved by choosing the appropriate distance between the patient who uses the mechanical device and the screen.

Another feature is portability of the device. The therapist can take the rehabilitation device to patient's home and reconstruct it in an easy way without worrying about wires. Using wires in the rehabilitation device can increase the probability of cutting them because of the mechanical movements of the device. As a result, this will reduce the reliability of the device.

The communication system in the rehabilitation device which is shown in Figure 5, consists of a controller (Arduino), XBee RF modules and interfacing circuit with the computer (XBee Explorer Dongle).

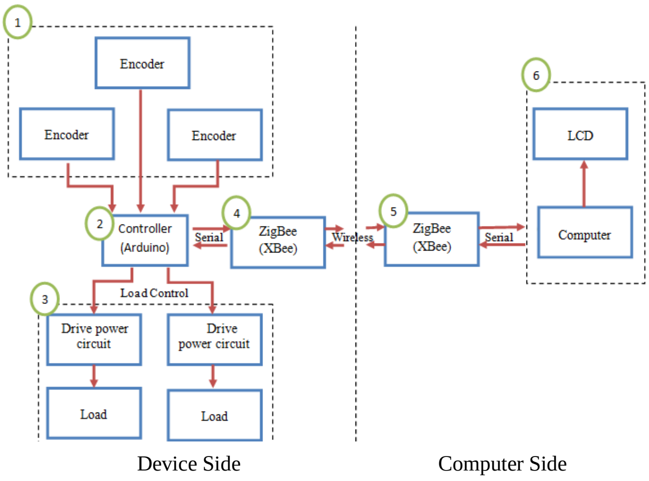

Figure 5: Communication System Block Diagram

VI. SOFTWARE SYSTEM

Stroke patients are typically seen for one or two half-hour sessions per day [12]. It was concluded from discussions with physiotherapist Dr. Akram Amro [13] that one session per a day with thirty minutes divided into two parts: about ten minutes for one of the reaching targets games, and the rest is for the following paths games.

Collect Money Game (CMG) is an example of the reaching targets games as shown in the left panel of Figure 6. In this game, the patient tries to move his/her arm in order to catch random targets.

Steady Hand Game (SHG) is an example of the following path games as shown in the right panel of Figure 6. The patient tries to follow the rod in order to finish the path and lead to the target with the least collisions as possible. The rod starts to be thicker as progressing in the game.

Figure 6: Left panel: CMG. Right panel: SHG

Both games are chosen for therapeutic session. They will be designed to get effective and correct therapeutic exercises. In addition, they will be enhanced to get more motivation and some usage of the cognitive skills.

One of these games is concerned with measuring the therapeutic level, and evaluates the patient's progress. For that reason, this game will be played at the beginning of each therapeutic session.

The game has ten different levels. A patient who finishes a level for three full successive sessions (contains CMG and SHG) without any problems will move to the next level. The main factors between the levels of the game that will change are: 1) The produced load (the maximum added load is 5 N.sec/m [6], [9]), 2) The time needed and the movement's speed to reach a goal. 3) The complexity of motion (targets positions in CMG, wire shape in SHG) and 4) The device configuration (horizontal, vertical or inclined).

On the other hand, the therapeutic process should store and retrieve the patient information and therapeutic progress, which can be achieved by a suitable data management system.

Moreover, the software system must control the signals that come from the sensors, represent it on the LCD Screen, and send the suitable signals to control the load, because all of the project's parts must work simultaneously in real time, to achieve the synchronization.

The user of the system (patient, physiotherapist or even the system administrator) will be allowed to access the patient's profiles, games options, and the device settings by graphical screen that is easy to use. The keyboard or the mouse of the computer can be used directly to enter the user interface screens or to modify the onscreen components.

Some of the evaluation methodologies for the patient progress are: 1) Section C of Rivermead Motor Assessment which is a therapist tool to evaluate the patient's therapeutic case by asking the patient to do fifteen simple arm exercises, and evaluate each movements independently [14]. 2) The progress reports that record the patient's parameters while he/she is playing the therapeutic games. Some of these parameters are the maximum and minimum angles for both the elbow and the shoulder joints which represent the range of motion for these joints, the movement speed of the elbow and the shoulder [15], the average patient’s reaction time and the maximum load that the patient can withstand with which indicates the muscles strength. 3) The games results and the progress of these results [16]. In Collect Money Game (CMG), the patient's performance is evaluated by a progress report that records the number of reached targets and reached bonus targets. However, in Steady Hand Game (SHG) the performance is evaluated by another progress report that records the number of collisions and the percentage of valid points, the number of points located on the ideal path and the completion time [17].

In order to enhance the patient's attention, motivation and motor recovery through brain plasticity, the therapeutic exercises is required to provide patients with some types of feedback such as visual, haptic, auditory and performance feedback.

CMG focuses on the attention and reaction cognitive skills. On the other hand, SHG focuses on the attention and concentration skills to avoid the collisions with the wire. SHG requires some perception skills that are used to choose the correct path through the whole wire to reach the target. It will be updated in a way to include the memory cognitive skills. Figure 7 explains the idea. A picture will be shown on the screen at the beginning of any level, it will then disappear after a short time. A wire will be shown on the screen with the previous picture but this time with new one. Each picture will be placed in different locations on the screen. The patient must move his/her arm navigating the wire and choose the correct target through the correct path.

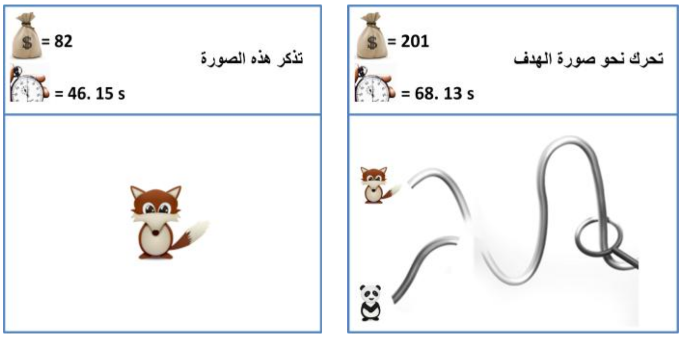

Figure 7: Enhanced SHG

As progressing in the session, the device configuration angle can be changed manually. This will affect the camera position (eye position) with respect to the game's objects only as shown in Figure 8. This allows patients to play the therapeutic games in different arm's positions.

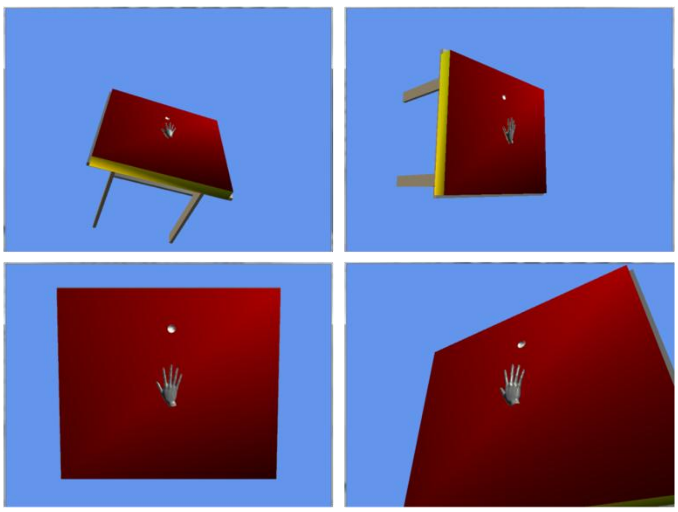

Figure 8: Different snapshots from different positions in CMG game

To locate the position of the hand in the workspace on the LCD screen, it is required that after each sample reading to map the joints' angles of the device on the game's window on the screen.

The device workspace is 800 mm width ranged between (-400 mm and 400 mm), and 400 mm height ranged between (350 mm and -750 mm), where the zero point is 550 mm on the y-axis away from the workspace origin point. On the other hand, the game's window is 800 pixel width, and 600 pixel height. The zero point is at the top left corner of the screen as shown in Figure 9. Suppose that $(\acute{x}, \acute{y})$ is the onscreen point, then:

$$\acute{x} = x + 400 \tag{1}$$

$$\acute{y} = 600 - ((y - 350) * 1.5) \tag{2}$$

where X and Y are the coordinate position and are derived in Appendix A.

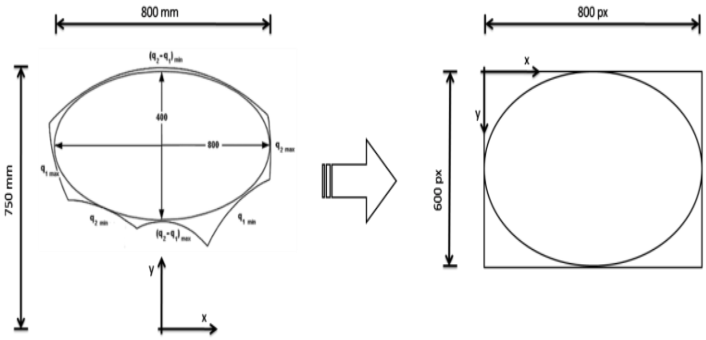

Figure 9: Left panel: The workspace of device. Right panel: The screen workspaces

VII. Conclusion and Future Work

It has been concluded that there is a need for virtual rehabilitation robots in Palestine. These robots can assist therapists during rehabilitation sessions to get the maximum possible benefit to patients.

Adding the third degree of freedom (configuration angle) could be useful for training different set of muscles with different exercises' levels in the rehabilitation session. This new feature allows the transition from designing two dimensions games to design three dimensions games.

Building dampers will be base on semi-active dampers type. This will allow controlling the load at real time without annoying the patient's interaction with the virtual environment.

After implementing the whole device, it should be tested on real cases under the supervision of therapists. And with the ability to design and install other types of games, more exercises can be done using this device to include other types of impairments in addition to strokes.

Appendix A: Kinematic analysis of the manipulator

The following equations describe the coordinates of the end-effector in the robot coordinate system as a function of the joints' angles:

$$X = (L_1.\cos\Theta_2 + L_2.\cos(\Theta_2 + \Theta_3)).\cos\Theta_1 \quad (A.1)$$

$$Y = L_1.\sin\Theta_2 + L_2.\sin(\Theta_2 + \Theta_3) \quad (A.2)$$

$$Z = (L_1.\cos\Theta_2 + L_2.\cos(\Theta_2 + \Theta_3)).\sin\Theta_1 \quad (A.3)$$

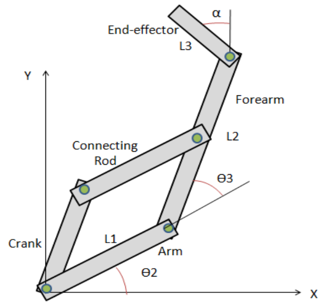

Figure 10: Top view of the manipulator in two dimensions before simplification

Where Θ_1 is the configuration angle. The crank and the connecting rod have no effect on the position of the end-effector which can be excluded from the analysis. To simplify the position equations, it can be assumed that the manipulator has two links only (Arm and Forearm) since the angle of the end-effector link (α) is constant and equals to 36.5˚.

The relationship between rotational speed of the joints and hand speed is

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix} = J \begin{bmatrix} \dot{\Theta}_2 \\ \dot{\Theta}_3 \end{bmatrix} \quad (A.4)$$

The Jacobian matrix of the kinematic transformation:

$$J = \begin{bmatrix} (-L_1.\sin\Theta_2 - L_2.\sin(\Theta_2 + \Theta_3)).\cos\Theta_1 & -L_2.\sin(\Theta_2 + \Theta_3).\cos\Theta_1 \\ L_1.\cos\Theta_2 + L_2.\cos(\Theta_2 + \Theta_3) & L_2.\cos(\Theta_2 + \Theta_3) \\ (-L_1.\sin\Theta_2 - L_2.\sin(\Theta_2 + \Theta_3)).\sin\Theta_1 & -L_2.\sin(\Theta_2 + \Theta_3).\sin\Theta_1 \end{bmatrix} \quad (A.5)$$

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