## BEN-GURION UNIVERSITY OF THE NEGEV FACULTY OF ENGINEERING SCIENCES DEPARTMENT OF INDUSTRIAL ENGINEERING AND MANAGEMENT

## A VIRTUAL REALITY-BASED TRAINING SYSTEM FOR ERROR-AUGMENTED REHABILITATION TREATMENT IN PATIENTS WITH STROKE

## THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE MASTER OF SCIENCES DEGREE

## LILY SROR

## UNDER THE SUPERVISION OF Prof. SIGAL BERMAN

SEPTEMBER 2019

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Signature of student:	Date:	26/9/2019
Signature of supervisor: Sigal Berman	Date:	25/9/2019
Signature of Chair of the Graduate Studies Committee: 322 3406	Date:	28/9/2019

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#### Abstract

Stroke is the leading cause of upper limb long term motor disability. However, current upper limb rehabilitation procedures often do not lead to full recovery. In this research, we developed a method and system for innovative treatment of motor limitation in the upper limbs, following a stroke. This method was based on adding an error at the joint level together with motor control theory. The goal of the training was to achieve a dynamic mapping of muscle-level control mechanisms. We hypothesized that adding an error at the joint angle level will increase the active control zone of the joint, thereby increasing the patient's ability to generate voluntary movement. The system for applying this method, included three components: a passive armrest that supports the arm against gravity, a motion tracking system using Kinect, and software that provides the workspace and visual feedback. In the present work we focus on the virtual reality environment.

The proposed system required software that can be projected onto a screen with a virtual hand matching the patient's movement, so that we can manipulate it by reducing 10 degrees from the joint angle(awkward language). In addition, the system should include a game environment that encourages the player to rehearse an arm extension action. The task of the game is to reach out to a spherical target displayed on a horizontal plane.

Prior to training, the workspace calibration is performed to ensure that the patient is able to reach the targets. A visual arm was displayed on the screen in front of the patient and moves according to information from the Kinect sensor. For the purpose of examining the system, it can operate with, or without, a 10-degree reduction from the elbow angle. The outreach task is time limited, while time can also be adjusted to the patient's capabilities. Positive visual feedback was provided for each success of reaching the ball. To monitor patient progress, the system saved the duration of time it takes the patient to reach each target.

A system validation trial was conducted with healthy participants to test the coherence of operation with the system. 21 participants were divided into two groups, of which trained with or without an error for 30 minutes. After the training, the participants of both groups were tested without an error. The measures examined were the NASA TLX questionnaire, which measures cognitive workload, average reaching duration, and success rate. The cognitive workload and the success rate were similar in both groups. However, the mean reaching duration was longer in participants who trained with an error, than in participants who trained without an error. This indicated that the participants who trained with an error had an after-effect. Indeed, it is yet unclear if a similar after-effect will be exhibited by subjects with stroke and if it will demonstrate a persistent change in their motion patterns.

Keywords—virtual reality, error augmentation, stroke, motor rehabilitation

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## Abbreviations

CSI	Composite spasticity index
DAT	Data operators
ER	Error augmentation
FM	Fugl-meyer
JEA	Joint error augmentation
LME	Linear mixed effect
MAS	Modified Ashworth scale
NASA TLX	NASA task load index
TSRT	Tonic stretch reflex threshold
VR	Virtual reality
WMFT	Wolf motor function test

## 1. Introduction

## 1.1 Error augmentation as a possible technique for improving upper extremity motor performance after a stroke

Annually, thousands of people experience stroke worldwide. Stroke may cause motor impairments which limits daily functions. Only 33–70% of patients regain useful arm function after what stroke. (Huang, Krakauer 2009). Restoration of arm-hand movement is critical for independence (Molier, Prange et al. 2011). Conventional neuro-rehabilitation treatment seems to have little impact on resolving the impairment over the natural recovery (Huang, Krakauer 2009). A main key for the restoration of motor control in stroke survivors is large amount of practice (Abdollahi, Case Lazarro et al. 2014, Patton, Stoykov et al. 2006). There has been a growing trend toward using interactive technology (Abdollahi, Case Lazarro et al. 2014), in addition to traditional rehabilitation methods for enhancing motor recovery.

A common complication of stroke is motor spasticity, characterized by velocity dependent, hyper-excitability of the muscle stretch reflex (Sommerfeld et al. 2004). It is a common symptom after stroke, arising in about 30% of patients, and usually occurs within the first few days or weeks (Mayer, Esquenazi 2003). However, the onset of spasticity is highly variable and can occur in the short-, medium- or long-term post-stroke period (Ward 2012). A study by Wissel et al. showed that 25% of patients with stroke suffer from spasticity within the first 6 weeks of the event. They also observed that spasticity primarily affects the elbow (79% of patients), the wrist (66%) and the ankle (66%) (Wissel, Schelosky et al. 2010). In the upper limbs, the most frequent pattern of arm spasticity is internal rotation and adduction of the shoulder coupled with flexion at the elbow, the wrist and the fingers.

One therapeutic strategy for dealing with said spasticity is Error Augmentation (EA). It is a technique that relies on a robotic interface, which uses erroneous feedback to enhance motor recovery after neurological damage. In EA, the system magnifies errors in a patient's movement from a desired route (Rozario, Housman et al. 2009), or changes the visual or haptic feedback of the movement trajectory. The presence of this error forces patients to adjust movement parameters (speed and amplitude) as they counteract the error-driven disturbance to the movements. Outcomes for EA training has been disappointing in terms of functional improvement (Israely, Carmeli, Alexoulis-Chrysovergis, Weightman et al. 2016). Hence, motor learning process and techniques require an innovative direction that will lead to better results.

## 1.2 Objectives and contribution

The goal of the project was to investigate the effect of Joint Error Augmentation (JEA) treatment for upper limb rehabilitation in subjects with stroke. JEA treatment refers to insertion of error from a desired trajectory applied to the elbow joint. The development of training methods based on motor control theory is fundamental to the successful implementation of rehabilitation robotic systems. This research is proof of a principle study with patients in two rehabilitation centers. ? The tested hypothesis was that JEA applied to the elbow joint range will lead to an increase in the patient's active control zone at the elbow and their ability to perform isolated voluntary movement.

The scope of this study is a system development followed by a validation experiment. The system is comprised of three modules, an iterative VR game, a passive supporting manipulator, and a tracking system which creates a visualization of the subject performing a task. The system is designed to test motor rehabilitation using JEA technique applying on the elbow joint at a horizontal movement.

A simple VR game with a reaching assignment was developed for motivating training. The game was adaptable to patient capabilities, based on the assessment of his/her active control zone for isolated elbow motion. The patient was presented with reduced or actual visual feedback calculated by fusing the position of the robot with input from a Kinect camera (essential for attaining required precision). The game included a calibration stage in order to ensure that it is capable for patient's abilities. The patient was presented with distorted visual feedback calculated by input from a Kinect camera. Optimization processes were performed for attaining required precision. The validation experiment was performed with healthy subjects to confirm that the perceived workload was similar with or without error at the observed elbow joint, but movement performance outcome was different between the two groups.

The passive manipulator was built with the help of Mr. Noam Peles, an engineer at BGU. Prof. Sigal Berman was responsible for the optimization of the tracking system with extended Kalman filter. My area of responsibility was developing the environment with virtual reality and conducting a validation experiment. Excerpts of this work were presented in poster presentation at the "International Conference on Intelligent Robots and Systems": Low-cost virtual reality system with passive arm support for stroke rehabilitation in 2018 in Madrid. At the "International Conference on Virtual Rehabilitation2019" in Tel-Aviv: Virtual Reality-Based Training System for Error-Augmented Treatment in Patients with Stroke. In addition, a presentation was conducted at the IEM Annual Conference 2019.

## 1.3 Work Scope

This project is part of a research collaboration with McGill University in Montreal, Canada. The current stage focuses on the development of the system, and its validation test. In the next phase of the research, data will be recorded from 24 patients with moderate-severe stroke, 6 per year. Subjects will be randomly allocated to two groups. One control group (regular feedback) and one group will receive JEA feedback (randomized with catch trials). Clinical assessment was conducted (Fugl-Meyer Assessment, Composite Spasticity Index measuring upper limb impairment, and streamlined Wolf Motor Function Test to assess functional activity level). The measures are presented in appendix 1. The subjects received a single long training session with 150 repetitions. The primary outcome measure was change in the Tonic stretch reflex threshold (TSRT).

#### 1.4 Outline

The rest of this thesis is organized as follows: Chapter 2 presents a literature review. Reviewed topics include stroke, motor impairment after stroke, and spasticity. This is followed by an explanation on the Enhance project as an example of motor rehabilitation that concerns spasticity. Then, a review of the error augmentation (EA) technique and virtual reality as a way to implement ER treatments. Chapter 3 describes the methodology and the components ensemble system. Chapter 4 describes a validation experiment for the system in which we examine the effect of the system on healthy subjects.

## 2. Literature review

#### 2.1 Overview

The literature review scanned concepts related to stroke rehabilitation with VR and existing interventions, with specific attention to error augmentation treatments. Section 2.2 provides background on the stroke disease. Section 2.2.1 focuses on the remaining physical limitations of the survivors. Section 2.3, focuses on the phenomenon of spasticity caused by a stroke, including an example of the Enhance project that investigates treatment considering spasticity. Afterwards, a review of virtual reality is presented as a beneficial tool for motor rehabilitation and error augmentation technique for expanding the control range while amplifying errors from the desired trajectory. Section 2.4 explains the rationale for the current work which is based on the referent control theory.

#### 2.2 Stroke

A stroke arises when blood flow to part of the brain is interrupted or reduced. As a result, brain cells lack oxygen and nutrition which cause brain cells to die. This condition damages the brain and abilities controlled by that area such as memory and muscle control are lost (Jamaludin, 2019). In 2017, the World Health Organization (WHO) published that stroke accidents are the second leading cause of death. More than 15 million people experience stroke every year and two-thirds of them have a permanent disability (Benjamin, Muntner et al. 2019).

Typically, the consequences of stroke are hemiplegia and hemiparesis. Hemiplegia is the condition in which one-side of the body becomes paralyzed. Hemiparesis is a condition of one-sided weakness. Roughly 80% of stroke survivors have hemiparesis <sup>1</sup>. Losing muscle control impairs quality of life. Basic daily abilities such as walking, drinking, eating, dressing, and grabbing objects are damaged (Dobkin 2004).

Motor impairment and muscle control could be improved by the use of activity movements involving repetitive tasks (task-orientated and task-variegated), which result in improving motor skills and muscular strength by preventing muscle spasticity, muscle atrophy, and osteoporosis

<sup>&</sup>lt;sup>1</sup> <u>https://www.stroke.org/</u>

(Dobkin 2004). Previous research concludes that beside rehabilitation procedure, personal motivation and rehabilitation environment can influence the process of treatment.

## 2.2.1 Motor impairment after stroke

Motor skills are one of the most significant areas affected by stroke. The patients may have disabilities ranging from a mild to severe degree, affecting one hemisphere or to both. Moreover, the paralysis can be expressed in different levels: the face or neck area, trunk and upper limbs or lower limbs. Hemiparesis defined as muscular weakness or partial paralysis restricted to one side of the body. It is an impairment present in 88% of stroke patients, affecting lower and upper limbs. Six months after stroke, about 38% of patients lightly recover in the arm and only 12% show full recovery after conventional rehabilitation therapy (Twitchell 1951).

Many of the activities we do during the day involve the upper limbs such as eating, dressing, and writing. Their use is not only associated with the use of everyday instruments but also with the contact with the world and the way we interact with other people. The accomplishment of these tasks requires sequences of complex movements that integrate the activation of appropriate muscular groups and the sensorimotor coordination of the hands, which translates into an effective functional action. Grasp and manipulation are strategies of movement that are mainly affected in stroke patients. Recent studies have found that recovery is minimal in some individuals, particularly those with a flaccid paretic limb in the first few weeks. This is why dysfunction in upper limbs is a major clinical, economic, and social problem for neurorehabilitation teams. Hemiparesis on upper limb usually affects the hand, causing weakness and spasticity, leading to decreased movement precision, muscle fatigue, lack of coordination, and an impaired ability to grasp objects, having a great impact on daily living activities (Ward, Kelly et al. 2015). Impairments such as decreased motor impulse, lower frequency of neuronal activation, poor sequencing/coordination of segmental movements, and sensory deficits have a marked influence on the functional performance of the upper limb. Muscle weakness and loss of manual dexterity may be accompanied by the development of soft tissue changes and shoulder pain.

Many studies have shown that increased therapy time in the upper limbs during the acute phase reduces associated impairments and improves function satisfactorily from a clinical standpoint. This must be related to an intensity and dose of therapy appropriate to generate substantial changes. It has been shown that patients have better motor function when performing a specific task involving a useful interaction with an object. Practice of strengthening exercises and functional actions is important after stroke as for anyone attempting to gain strength and ability in motor actions (Langhorne, Bernhardt et al. 2011).

## 2.3 Spasticity

Spasticity is a defined as a motor disorder characterized by a velocity-dependent increase in tonic stretch reflexes (muscle tone) with exaggerated tendon jerks, resulting from hyper excitability of the stretch reflex" (Sommerfeld et al. 2004). Spasticity is one of the most common sequelae of central nervous system lesions and stroke. Accurately measuring spasticity can benefit physical therapy treatments and patients with stroke condition evaluation (Mullick, Musampa, Feldman and Levin, 2013). Lance's definition of spasticity (1980) suggested that the threshold of the stretch response should be the focus of measurement. Because of confusion in the operational definition of spasticity, there is still a lack of consensus regarding how spasticity may be best measured (Calota, Feldman, Levin, 2008). Disorders in the specification and regulation of stretch reflex thresholds by the central nervous system can account for both spasticity and disordered muscle activation, including muscle weakness in these patients (Levin et al., 2000; Musampa et al., 2007). Tonic stretch reflex threshold (TSRT) is a theoretical threshold joint position that may be a more representative measure for subjects with moderate to high spasticity. Further improvements are suggested for the portable device in order to quantify all the levels of spasticity (Calota, Feldman, Levin, 2008). TSRT can measure spasticity well, especially for subjects with moderate to high levels of spasticity (Calota and Levin 2009).

"One example of rehabilitation that considers spasticity is the ENHANCE project, an international project which operates in centers in Israel, India and Canada. The project focuses on enhancing brain plasticity for sensorimotor UL recovery in spastic hemiparesis of post-stroke patients. A training program is proposed which combines current knowledge about brain plasticity and motor control and includes VR combined with non-invasive brain stimulation to enhance motor learning. The training incorporates personalized transcranial Direct Current Stimulation (tDCS), which is a form of neurostimulation that uses constant, low current delivered to the brain area of interest via electrodes on the scalp, to balance cortical hypo/hyperexcitability. In addition, it involves personalized reaching training, based on the

identification of the individual's disorders in spatial threshold (ST). The training approach is guided by identification of the elbow angular zone in which spasticity occurs ('spasticity zone') and limiting reaching training to the zone in which active control is preserved ('active control zone') (Levin, Baniña et al. 2018). The presented study relies on the same principles as for the Enhance project. We aim to find a treatment for upper limb recovery. while considering the phenomenon of spasticity.

## 2.3.1 Virtual Reality for stroke rehabilitation

## 2.3.2 Error Augmentation

A therapeutic technique that involves a robotic interface is error augmentation (EA), which utilizes erroneous feedback to enhance motor recovery after neurological damage. In EA, the computer singles out and magnifies errors in a patient's movement from a desired route (Rozario, Housman et al. 2009) or changes the visual feedback of the movement trajectory. The presence of this error in the visual systems forces patients to strengthen their control as they counteract the error-driven disturbance to the movements.

Several lines of reasoning justify that augmenting error may enhance motor learning, Nevertheless, this feedback is sometimes counterintuitive and differs from the standard approach of rehabilitation (Wei, Bajaj et al. 2005). First, error drives learning and is believed to be central to adaptation and skill acquisition in human movement, as justified by models and artificial learning such as neural network (Patton, Stoykov et al. 2006, Wei, Bajaj et al. 2005). Since intrinsic feedback mechanisms are often impaired after a neural damage (Molier, Prange et al. 2011), providing augmented feedback by making errors more noticeable to the senses, is thought to be beneficial. A patient will learn quicker when the error is magnified (Huang, Krakauer 2009). Finally, larger errors are likely to increase motivation to learn (Molier, Prange et al. 2011, Wei, Bajaj et al. 2005) by making even small errors seem meaningful.

Combining machine-assisted training to the rehabilitation processes yield additional benefits. Machine-assisted training is more accurate, capable of being carried out for longer periods of time, capable of automatically recording measurements, and produce a wide range of forces and motions (Patton, Stoykov et al. 2006). Therefore, applying this relatively new method using human–machine interactions for motor learning offers exciting new prospects for regaining upper limb motor control after neural injury (Israely, Carmeli 2016). A rehabilitation

system that implements EA technique requires a visual (or haptic) feedback, which can be generated using a virtual reality (VR) technologies.

Studies examining the lower extremity EA method show significant short-term improvement compared to subjects who received traditional, error-free treatment (Tyrell, Helm et al. 2015, Kao, Srivastava et al. 2013). In contrast, when it comes to upper limb movement, improvement is not satisfactory (Israely, Carmeli 2016, Alexoulis-Chrysovergis, Weightman et al. ). This might be due to a large variety of movements that we want to perform with our arm. Therefore, the direction of implementing the error to the joints rather on the target is a promising direction.

## 2.3.3 Virtual Reality

Many innovative treatment techniques have arisen to improve the effectiveness of stroke recovery, including robotic technologies, human computer interfaces, or therapies using non-invasive brain stimulation. These treatments have shown encouraging results (Hatem, Saussez et al. 2016). Numerous treatments are available and aimed at accelerating the natural course of recovery. Initially, the treatments were targeted to improve cerebral perfusion in the acute stage. In the following phases, from the subacute to the chronic stage, treatment strategies were geared to improve functional recovery through enhancing neuronal plasticity, relearning processes, and functional reorganization. Interdisciplinary complex rehabilitation interventions represent a pillar of post-stroke rehabilitation to recover lost function and to increase the autonomy of stroke patients (Langhorne, Legg 2003).

Technology-supported rehabilitative training approaches include the adjunction of immersive environments while training, robotics technologies, or brain-computer interfaces. Virtual Reality (VR) are technological developments in the game where a player will be connected with the virtual environment so can motivate the spirit's player to complete a game. Rehabilitation based on VR has become a popular platform among researchers and rehabilitation specialists in replacing the conventional stroke rehabilitation which is repetitive and uninteresting (Yeh, Stewart et al. 2007). It is an effective way of establishing a variable and stimulating environment, allowing the patient to engage in meaningful and motivating therapeutic activities (Prashun, Hadley et al. 2010). Despite virtual rehabilitation, many have flaws, but nevertheless have shown advantages (Trombetta et al. 2018). On the other hand, research has shown that rehabilitation using movement sequence is better than using random sequence, even though this result is still in the research phase.

## 2.4 Referent control theory

Error augmentation technique relies on referent control principles. The source of motor actions is the shift of the threshold position of the appropriate body segments, i.e. the virtual position at which muscles are silent but deviations elicit activity and resistive forces (threshold position control) (Feldman, et al.2007). Threshold position control is a well-established empirical phenomenon that shows that motor can reset the threshold limb position (Feldman and Orlovsky, 1972; Nichols and Steeves, 1986). Any deviation of the body from the threshold position, elicited either by external forces acting on the body or by central resetting of the threshold position, results in a change in proprioceptive signals to motoneurons. These signals facilitate motoneurons of those muscles that resist the deviation of the body from the threshold position. The proprioceptive response to the deviation also elicits activation of interneurons of reflex loops, some of which mediate interactions between muscles (Feldman, Goussev, Sangole and Levin, 2007). The importance of threshold position control is also emphasized by findings that lesions of different brain structures in stroke survivors limit the range of threshold regulation, resulting in numerous motor deficits such as muscle weakness, spasticity, as well as impaired coordination (Levin et al., 2000; Mihaltchev et al., 2005).

## 3. Stroke rehabilitation with joint error augmentation

### 3.1 Overview

We hypothesized that JEA applied to the elbow joint range will lead to an increase in the patient's active control zone at the elbow and thus in his/her ability to perform isolated voluntary movement. In order to examine this method, we developed a rehabilitation system that implements JEA applying to the elbow joint. The system is personalized to a stroke patient's reduced abilities and enables training on a specific task with erroneous visual feedback. The system is comprised of three modules: Virtual game developed with Touch Designer<sup>TM</sup> (Derivative. Canada), a node based visual programming language for real time interactive multimedia content. The additional modules are a passive supporting manipulator and a perception system responsible for tracking the patients' arm and maximizing accuracy. The methodology is described in section 3.2; the development of the virtual environment is described in section 3.3. The additional system components are described in section 3.4. Figure 1 shows the system setup in Soroka University Medical Center's physiotherapy department.



Figure 1 - System setup

## 3.2 Methodology

The developed a system included a game environment. This environment involved visual feedback, as ten degrees were reduced from the elbow joint angle i.e. horizontally, the elbow angle of the virtual arm is ten degrees less than the actual movement of patient's hand. Thus, the patient had to reach out more openly to reach the target. By introducing the error, we aimed

to defer the spastic contraction of the antagonist muscles (the flexors) during the elbow extension. In that we hoped to increase the control zone of the elbow joint. We aimed to prove the patient's range of motion with the help of the indices listed in appendix 1. Figure 2 illustrates the execution of the movement following EA.



Figure 2 - Torque/angle. Torque/angle characteristics of individual agonist (extensors, blue trace) and antagonist (flexors, red trace) muscles of the elbow joint and their threshold angles (RE, RF respectively). The joint characteristics are depicted by the dashed line between them. A. When the actual target (black circle) is perceived at position b, subject extends the elbow by shifting the joint angle characteristic in the same direction (arrow) to position b, B. Visual feedback indicates to the subject that the distance moved by the elbow undershoots the target (red circle). C. To correct the perceived error, the subject moved the joint angles characteristics further to the right to position C. (Sror, et al. 2019)

## 3.3 Virtual environment

Joint error augmentation requires accurate visualization of the entire arm, with the ability to include an error in the presented joint angle. The visualization should invoke a high degree of presence, so that the participant will accept the visualized arm position as representing his/her actual arm location, despite conflicting input from his/her proprioception. The game for training should encourage a functional gross arm motion task which is suitable for patients who have not yet regained fine motor skills. The game should be motivating, but the visual scene should not be overwhelming, since the patient's perception capabilities may be reduced. The training range should be suitable for performance in the horizontal plane facilitated by the supporting manipulator.

The virtual environment was first developed with Unity<sup>TM</sup> (described in appendix 3). A second generation was developed using TouchDesigner<sup>TM</sup> software (Derivative, USA). Operators objects in a project are represented as nodes in the user interface and are connected in order to create procedural effects and animation. Each operator is customized with a unique set of parameters and flags that control its operation and processing. The program runs the code periodically. Texture operators are image-based operations that are GPU accelerated. Data in TOPs can be scaled to any resolution, limited only by the amount of RAM available on a system's graphics card<sup>2</sup>. TouchDesigner is an optimal platform for the development of our rehabilitation environment because it enables instant data manipulation and application to the graphical objects.

A stationary reaching task was designed according to these specifications in which targets are presented within a horizontal plane. The virtual camera is placed to emulate a camera behind the subject at a tilt angle of  $45^{\circ}$ , emulating a first-person view. A full arm model was presented on the screen, based on the tracked motion with (or without) an inserted  $10^{\circ}$  errors to the elbow angle. The reaching task was time-limited, and the environment facilitates adaptation of the time allocated for reaching a target during any point in the training. A motivational icon

<sup>&</sup>lt;sup>2</sup> <u>https://docs.derivative.ca/Intro\_to\_TouchDesigner</u>

was presented above the participant's hand upon each successful reach, and every 30 reaches an encouraging message was presented on the screen.



Figure 3 - Development outline. The colors are meant to mark global variables, and link between a function and its chart. Diamond signifies a condition. Parallelogram signifies a function. Hexagon marks a beginning of a loop.

As seen in figure 3, the game manager begins with a hexagon that indicates a repetitive action. The game contains cycles of 30 targets each and lasts 30 minutes. Every frame, the program measures the distance between the target location to the hand. Distance smaller than a threshold of 0.12 cm indicated a success that operated the following actions: a beep sound, emoji appears on the back of the hand, the target disappears, and the duration is written to the out file. At the end of each cycle (30 targets), the visual feedback (described in section 3.3.4) appeared for two seconds on top of a darkened screen.

The position of the hand was calculated with the information of the Kinect operator. The dominant hand data (shoulder, elbow and wrist locations) was selected with a select node. Then, the position of the hand was calculated according to the continuation of a vector created from the elbow and wrist, followed by a Kalman filter which is described in Chapter 3.4. Eventually, in case of training with error, the error is inserted to the angle of the elbow joint (described in section 3.3.3). The target position subprogram is elaborated in section 3.3.1. and the UI in section 3.3.5.

## 3.3.1 Setting up the training range

The purpose of the virtual game was to reach and touch the appearing targets. Hence, the game requires positioning certain targets and measuring the distance between the hand and the target and compare it to a threshold. To do this, we placed the targets where the patient was capable of reaching. The range of control varies from patient to patient and therefore the initial calibration phase was required.

The game area was adjusted to the control zone of the subject. Prior to the training, a calibration procedure was performed for defining a patient-specific training zone. The subjects were required to fill up the area where they can reach by simply moving their hand across the surface. A trace of the locations was then shown on a black screen. Figure 4 shows the documentation of the locations that the subject touched to create targets for the game.



Figure 4 - Setting up training range stages. Respectively to work with Touch Designer: Green - CHOP operator, pink – DAT operator. Purpule - TOP operator. Expended in the following text.

The code received the hand position as the input. The location of the hand was calculated as a continuation of the vector created from the elbow and wrist and depicted in Figure 4. Then, a paint brush and canvas were created. The node 'combine' combined the brush and the canvas and node 'feedback' created a trace of the brush and presented it on the screen. All the purple nodes are type 'TOP' and they are displayed on the screen. The green nodes are user input. The reset button allows you to start the recording again for any event that requires it. At the same time, all 720 samples were recorded to a DAT type node. Using a manual python code, we projected the locations on a best fitted plane that minimizes the distances between the locations to the plane. Afterwards, thirty random targets were selected. A list of thirty locations was then created. Then, during the game, for cycle i the target that is indexed i was selected from the list. Figure 5 shows an example of subject's trace as shown on the screen.



Figure 5 - Patient's screen' calibration screen – trace example

## 3.3.2 Game visualization

The planning process emphasized creating a clean and simple environment, but at the same time providing all necessary information. The software must give a comfortable three-

dimensional feeling in terms of the arm visualization, player's point of view, and adjustment of light and color.

Joint error augmentation requires accurate visualization of the entire arm, with the ability to include an error in the presented joint angle. The visualization should invoke a high degree of presence so that the participant will accept the visualized arm position as representing his/her actual arm location, despite conflicting input from his/her proprioception.



Figure 6 - Virtual environment, patient screen. From top to bottom: Success rates, virtual hand, target, word of encouragement. The caption appears once for every 30 goals.

The virtual arm was modeled after a model of a human figure from which the rigid body parts are cut off. Then, the locations of the wrist, shoulder and elbow locations are applied on the virtual arm with adjustments of light and color. Figure 7 shows the process of creating the arm rig.



Figure 7 - Virtual arm visualization. Blue – GEO operators. Yellow – MAT operators.

First, we downloaded a body rig file and imported it with an import node. Boolean parameter of dominated hand (left or right hand) is imported from the UI. Section 3.3.5 describes the UI interface. Subsequently, we used an operator of the type clip to cut each body part and then a transform operator to move the geometry to the designated locations. Blue nodes are of the type 'SOP,' i.e., operators that can generate, import, modify and, combine 3D surfaces. We performed transformations and adjustments to create the illusion of a real arm. To create a modular environment suitable for training on each arm (left or right), we created a visualization of each hand individually. This was followed with a node of type switch to choose the arm that will be visible on the screen according to the UI input.

In addition to arm visualization, we integrated a game surface with horizontal and vertical lines to give a sense of depth to the game. A sense of depth is important because the player's movement is flat, and the screen is vertical. The surface is tilted to 45° degrees corresponding to the virtual camera. The virtual camera is basically the point of view of the player from which it overlooks at the game. We positioned it where the virtual player's eyes would be so that the patient looks at the screen comfortably as if they are looking at their own arms.

### 3.3.3 Error insertion

According to the method of the research, the virtual arm represents the patient's arm with a difference of ten degrees subtracted from the elbow joint. The input of the perception system were the filtered locations of the patient's arm. Then, as described in figure 8, on each frame we performed a calculation of the angle between the two vectors (vector 1-elbow to the wrist, vector 2 - shoulder to wrist), reduction of ten degrees of the angle, and finally, calculated wrist location. The size of the error is 10 degrees, so it was not to be clearly apparent but still large enough to lead to non-conscious changes in the players motion. The output of the process was the new wrist location. The new wrist location, together with the shoulder and elbow positions are the input to the virtual arm transformation parameters.



Figure 8 - Error augmentation development stages. White nodes indicate operations that were made using a manual Python code rather than a touch designer operator. Green nodes are of a 'CHOP'.

## 3.3.4 Exercise training feedback

One of the benefits of training with virtual environments is providing feedback which enables players to measure their progress in achieving set goals, or the development of their skills over time. Also, positive feedback helps to keep the player engaged (Burke, McNeill et al. 2009, Wei, Patton et al. 2005). The current developed rehabilitation environment gave the patient information about their performance in the game. First, when the patient was close enough to the target, the system played a beep sound, and a positive emoji appeared on the player's hand. Furthermore, at the end of every session of thirty targets, there was a comment on the bottom of the screen, which encouraged the player to keep training. If the success ratio was over 0.8, the feedback is "Incredible!!!"; if the success rate was between 0.6 to 0.8, the caption on the screen is "Great job!". Otherwise, the caption says, 'Keep working'.

## 3.3.5 Performance monitoring

Post stroke rehabilitation systems require the ability to monitor the patient's processes and performances. Also, for experimental purposes, we needed the system to record all information regarding the subject: success times, target locations and what targets the patient was able to reach. In addition, the date, level of difficulty (given time to reach the goal), with which hand played (right or left), patient code, therapist code and error information (with or without) was recorded. Practically all of the details mentioned are saved to a DAT and saved to an Excel file. The system required adjusting patient's parameters and tracking performances. We created a user interface (UI) for the therapist (presented in Figure 9) where they can fill in and adjust the following: date, Therapist ID, patient code, cycle time, error (no error state for experiment purposes), and training hand. Furthermore, we created buttons to operate the game and finish it for any reason that the patient might need to stop. We saved the following data to an out file together with the patient's performances. The name of the file contains the date, and the time (1 < time < 24).

Date	2.6.19			
Therapist ID	lily			
Patient Code	12			
Cycle Time	3			
Error	With			
Switch Hands	Right			
Start calibration				
Finish calibration				
Start training				
Finish training				

Figure 9 - Therapist's UI

## 3.4 Additional System components

## 3.4.1 Passive supporting manipulator

The passive supporting manipulator was modeled after an ergonomic computer desk armrest. Such devices support the arm while facilitating smooth horizontal movement. The manipulator has two links and three horizontal joints. The wrist was placed on a padded wrist holder and connected to the manipulator using a Velcro strap. The hand is free so that the participant can use it for making a task-relevant motion.

An effort was made to support comfortable motion through the workspace while keeping the manipulator small and straightforward. Three link-size configurations were tested (Figure 2). With the original armrest and the prototype, the motion range was limited, and task execution was uncomfortable. The second prototype facilitated smooth motion throughout the workspace while still having a small footprint. The manipulator was connected at the required vertical level to a supporting stand. The stand was connected to a large weight (approx. 50kg) for stability.

Version	Link 1 [mm]	Link 2 [mm]
Original arm-	122	111
rest		
First	170	150
prototype		
Second	170	185
prototype		

Table I -Manipulator link lengths (Sror, et al. 2018)

## 3.4.2 Motion tracking system

One of the main challenges in the development of the system was the accuracy of the arm position data. The system does not function correctly if the samples of the locations are noisy. The challenge was the minimization of random error in order to control the error of the elbow joint angle. In addition, the goal of the player in the game is to reach a target. It is necessary that the system know the exact location of the target and the hand location in order to compute the distance between them, incorrect calculation would lead to a frustrating game for the patient.

Motion tracking is based on the Kinect skeleton. A Kalman filter is used for attaining the required accuracy. The Kalman filter keeps track of the estimated state of the system and the variance or uncertainty of the estimate. The estimate is updated using a state transition model and measurements. As described in figure 10,  $\hat{x}_{k|k-1}$  denotes the estimate of the system's state at time step k before the k<sup>th</sup> measurement y<sub>k</sub> has been considered;  $P_{k|k-1}$  is the corresponding uncertainty.



Figure - 10 Kalman filter process<sup>3</sup>

Using the Kalman filter, we minimized the random error. As presented in Figure 11, The estimation of the shoulder model is based on an expected low amount of trunk motion, since the patient is supported to the back of the chair with Velcro straps. The prediction of the elbow position is based on rigid body assumptions, as the intersection point between the two spheres created by the shoulder / wrist location and the length of the bones as a radius. The estimation of the wrist is due to the wrist resting on the passive manipulator while also connected to a horizontal plane.

<sup>&</sup>lt;sup>3</sup> <u>https://www.wikiwand.com/en/Kalman\_filter</u>



Figure 11 - Movement assumption as a prior knowledge to the Kalman filter (Sror, et al. 2018)

## 4. System validation experiment

We conducted a validation experiment with healthy participants. The experiment examined whether the perceived workload was similar between the two groups, while the performance of the two groups was different. Group 1 - training on the environment with error, group 2 - training on the environment without error.

Our goal was such that the participants would not notice the EA while it would affect their movement. We hypothesized that the subjective measures (NASA TLX questionnaire) will be similar, but the performance level indices show a difference between the two groups. With this, we concluded that the error had unnoticeably affected their voluntary movement.

### 4.1 Participants

Our experimental group was composed of twenty-one healthy participants, students of Ben Gurion University of the Negev (BGU). The BGU Human Subjects Research Committee approved the study. All participants signed their informed consent. Experiments were carried out at the industrial engineering and management department. Participants had normal or corrected to normal vision and were randomly divided into two groups: Groupe 1 had 11 subjects (6 male) and Group 2 had 10 subjects (6 male). The average age of 26.2 years with a SD of 1.16. 12 of the students were males.

### 4.2 Apparatus

The subject was seated on a stable chair with a backrest and no wheels. The distance between the chair to the screen is 1.2[m], and the screen was located at the height of 1.5 [m]. The size of the screen presented to the subject is 50 [inch]. The passive manipulator was attached to a desk; the location of the table was adjustable to the side of the subject's dominated hand. Kinect sensor was located on top of the screen with an elevation of 40 [cm] to satisfy a better point of view on the working arm.

## 4.3 Task and Procedure

A training session started with a calibration stage which is elaborated in section 3.3.1 The game parameters of the game are adjusted to the subject's movement range. After the calibration, the subjects underwent training of 30 minutes (training set), with error for group 1 and without error for group 2. Every two seconds, the program presents a target on the surface within the movement range. The 30 locations of the training set were repeated for 30 times. The subject was asked to reach their hand to the target. Afterwards, the subject answered the NASA Task Load Index with google forms (presented in appendix 2). The NASA-TLX is a widely used, subjective, multidimensional assessment tool that rates perceived workload in order to assess a task or a system, or other aspects of performance. Finally, the subject performed another set of only thirty targets (test set) without error for both groups. This session lasted one minute.



Figure 12 - Experiment process

## 4.4 Analysis

The objective measurements of the experiment are the average duration and success rate. The mean duration was calculated for the 30 first target end 30 last cycles of the training set. For the first 30 samples of the training set, the 12 shortest times were chosen since all subject managed to reach at least 14 targets in the given time (2 seconds). For the 30 last targets of the training set, the mean duration was calculated for the 14 shortest times. For the same reason, on the test set, the mean duration was calculated for the 12 shortest times. The success rate was calculated as the ratio of the number of reached targets in each set and 30, since 30 targets were given in each set. The subjective measures of the experiment are integer answers (1-7) for each question per subject.

## 4.5 Statistical analysis

Statistical analysis was performed with R Studio IDE for R (version 3.5.2). P-values of <.05 and >.1 were used for inclusion or rejection, respectively.

Statistical analysis on the data of the training set was performed using a linear mixed-effect model (LME) while the type of treatment (with or without error) and the stage (before or after training) are fixed and the subject id is random.

Statistical analysis on the NASA TLX results was performed using a welch two-sample t-test because the sample size of each group is unequal. The test was performed on each dimension of the questionnaire separately to examine the differences between the groups on each aspect.

Finally, to compare the test set between the two groups, we used a t-test on the data of the duration and success rate of the subjects in the last 30 targets (as stated, without error for both groups).

#### 4.6 Results

For the training set, the duration of first 30 cycles was longer then last 30 cycles for both groups. Success rate was higher at the last 30 targets for both groups (table II, Figure 13).

	training set				
	Duration(sec/2)	success rate			
with error	before =.51(.08), after = .53(.09)	before =.64(.26), after =.77(.16)			
without error	before =.4(.2), after =.5(.06)	before =.35(.36), after =.86(.09)			

Table II- Training set results. Before – first session of training. After – last session of training.

There was no significant difference between the two groups (treatment with error and treatment without error). That means that the improvement of duration and success rate was independent from treatment type. Presented in Figure 13.



#### Figure 13 - Stage\*error effect plot

For the test set, the duration of group 1 was longer the group 2. The success rate was higher for group 1 (performed training set and test set on the same environment - with error). Scores are presented in table III and figure 14.

Duration (sec/2)		success rate (%)
Group 1 - with error	.42(.12)	.86(.09)
Group 2 - without error	.32(.09)	.76(.17)

Table III - Test set results

The success rate of the two groups were similar. There was a significant difference between the duration of the two groups. Reaches made by subjects from the group of training with error were slower compared to the group of training without error. The Welch t test shows a significant difference ( $t_{163, 18} = -2.48$ ; p < .05).



#### mean duration-test set

#### success rate- test set



Figure 14 - Test set data

In	the	case	of	sub	iective	measures:
			~	000		

error	mental	physical	temporal	performance	effort	frustration	Look feel
no	3.7(1.1)	3.1(1.64)	4.5(1.81)	5.4(.66)	2.9(1.22)	1.5(1.2)	5.5(1.2)
error							
with error	3.36(1.43)	2.82(.94)	4.82(.83)	4.82(1.03)	3.18(1.34)	1.82(1.34)	3.91(1.08)

#### Table IV - NASA TLX results

According to the results, there is no difference between groups on any question of the test. On the other hand, subjects from the group of treatment without error reported that hand visualization was better than the group of treatment with the error. The average was 3.7 on a scale of 1-7. The answers are presented in Appendix 2 and in Figure 15.



Figure 15 - NASA TLX data

## 4.7 Discussion

The hypothesis that the perceived workload would be similar between the two groups (training with error and training without error) but the performances will be different has been confirmed. A comparison of the results between the first and last training set shows learning, as expected. The learning curve of the two groups was similar. Only when the error group performed the test set on a different system than training (group 2 performed test set without error), we see a difference between the two groups. That is, the subjects of the error group learned something, and its movement changed as a result of the training. After the training set, they felt that they needed to open their elbow angle a little more than they needed, and that made a difference between the results.

In terms of the results of the NASA-TLX test, we see that subjects were unaware that there was some error in their movement or the movement of the visual hand on the screen. We learned that the visualization invokes a high degree of presence(?). The subjects accepted the visualized arm position as representing their actual arm location, despite conflicting input from proprioception.

Furthermore, we concluded that there was no difference between the groups considering all aspects of the questionnaire (level of performance, pace, mental effort, level of effort, physical difficulty, and frustration).

## 5. Conclusions and Future research

In this project, a motor rehabilitation system was developed. Movement restoration focused on arm control range movement at the horizontal plain. The game that has been developed is a target-reaching game that involved an elbow extension task, with a difficulty level that could be adapted to patient's capabilities. The system applies JEA to the elbow angle through the visual feedback. Proving the effectiveness of this method might be effective in the world of motor rehabilitation. A validation experiment with healthy subjects showed a difference between performance and similarity with the NASA TLX result, i.e. the results support that the system is likely to cause movement parameter adaptation among stroke patients.

The system was set up at the rehabilitation department at Soroka University Medical Center in Beer-Sheva, Israel. A pilot experiment is underway. A second system will be installed in Canada. Twenty-four sub-acute patients with sub-acute stroke (six weeks to three months' post-stroke) will undergo three thirty-minute training sessions on consecutive days. Half of the patients will receive visual feedback with error, and half will receive visual feedback without error. The Helsinki Committee approved the experiment in Israel at Soroka University Medical Center.

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## Appendix Appendix 1- Clinical measures

This section describes the metrics that will be used to measure the success of the process when performed among stroke patients. The clinical assessments that will be conducted are the Fugl-Meyer Assessment, the Composite Spasticity Index measuring upper limb impairment, and a streamlined Wolf Motor Function Test to assess functional activity level.

Many experts in the field of stroke consider the Fugl-Meyer (FM) Assessment to be one of the most comprehensive quantitative measures of motor impairment following stroke (Gladstone, Danells et al. 2002). The use of this assessment is recommended for clinical trials of stroke rehabilitation. This scale is designed in order to evaluate recovery in the post stroke patients. The FM scale is a 226-point multi-item Likert-type scale that are into 5 domains: motor function, sensory function, balance, joint range of motion, and joint pain. Each domain contains multiple items, each scored on a 3-point ordinal scale (0 = cannot perform, 1 = performs partially, 2 =performs fully). The motor domain includes items measuring movement, coordination, and reflex action about the shoulder, elbow, forearm, wrist, hand, hip, knee, and ankle. The motor score ranges from 0 (hemiplegia) to a maximum of 100 points (normal motor performance), divided into 66 points for the upper extremity and 34 points for the lower extremity. Similarly, there is a maximum of 24 points for sensation, 14 points for sitting and standing balance, 44 points for joint range of motion, and 44 points for joint pain. The FM assessment is best administered by a trained physical therapist on a one-time basis with the patient. It takes approximately 30 minutes to administer. (David J. and others, 2002) The Composite Spasticity Index (CSI) is a measure of upper and lower extremity spasticity that is suitable for use with patients with hemiparesis following stroke. The CSI measures the phasic stretch reflex by assessing the tendon jerk and clonus, and the tonic stretch reflex with assessment of resistance to passive movement of the limb. The tendon jerk measures hyper-reflexia by tapping the biceps, triceps, patellar or Achilles tendon (depending on the location of the spasticity being measured). The therapist should apply enough force to evoke a 'maximal' reflex jerk. This can be compared with the maximum tendon reflex elicited on the unaffected side. Resistance to passive stretch measures hyperactivity of the tonic stretch reflex by assessing the amount of resistance felt by the examiner when the passive muscle is stretched. This item incorporates the Modified Ashworth Scale 5-point ordinal scale, which is double-weighted (0 to 8) and measures the magnitude of the resistance to stretch at moderate speed (> 100 degrees per second). Clonus is assessed by the number of beats of clonus at the wrist (upper limb) or ankle (lower limb) when the hand or foot is rapidly flexed by the examiner.

The Wolf Motor Function Test (WMFT) is a laboratory-based test, measuring time to complete fifteen UE tasks and two strength tasks. The WMFT is typically administered to patients with mild to moderate stroke to assess the impact of specific interventions. Unlike other assessments for stroke, the WMFT tests a wide variety of tasks (progressing from simple to complex) and is composed of 3 parts: (1) time/the speed of the completion of the tasks, (2) functional ability/the quality of movement during the task, and (3) strength. The progressive tasks are relative to the number of joints used to perform the task, beginning with selective activation at the shoulder joint to complex but functionally relevant movements. The primary outcome measure is the mean or log mean WMFT score for the fifteen timed tasks, keeping the two strength task scores separate. Because of the skewed distribution of normative data, this test can differentiate patients who are considered higher or lower functioning among individuals with mild to moderate stroke as defined by wrist and digit-active range of motion. Moreover, the test is not influenced by whether the affected limb is dominant.

## Appendix 2 - NASA TLX

The NASA Task Load Index (NASA-TLX) is a widely used, subjective, multidimensional assessment tool that rates perceived workload in order to assess a task, system, or team's effectiveness or other aspects of performance. It was developed by the Human Performance Group at NASA's Ames Research Center over a three-year development cycle that included more than 40 laboratory simulations. It has been cited in over 4,400 studies, highlighting the influence the NASA-TLX has had in human factors research. It has been used in a variety of domains, including aviation, healthcare and other complex socio-technical domains<sup>4</sup>. This section describes the TLX questionnaire. Figure 16 shows the original questionnaire. Figure 17 shows the translated questionnaire given to our subjects by Goggle Docs. Finally, Table 5 shows the raw data of the results.

<sup>&</sup>lt;sup>4</sup> <u>https://en.wikipedia.org/wiki/NASA-TLX</u>

## NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task					Da	ite						
Mental Demand		How	/ men	tally	dem	and	ling	wa	s the	e tas	sk?		
Very Low									Ver	ry H	ligh		
Physical Demand How physically demanding was the task?													
				I							I		
Very Low									Ver	уH	ligh		
Temporal Demand	How hur	ried	or rus	hed	was	the	pa	ce o	of the	e tas	sk?		
Very Low									Ve	ry F	ligh		
Performance How successful were you in accomplishing what you were asked to do?													
				I	I		I			I	I		
Perfect										Fail	ure		
Effort How hard did you have to work to accomplish your level of performance?													
				Ι	1					I	1		
Very Low									Ver	уH	ligh		
Frustration	How ins and ann	ecure	e, dis I were	coura you?	ged	l, irr	itate	ed, s	stres	sec	i.		
Very Low									Ve	ry H	ligh		

Figure 16 - NASA TLS Source

כמה דרשה פעילות מבחינה נפשית (חשיבה, ריכוז, אחריות וכו') ?														
	7	6	5	4	3	2	1							
הרבה מאוד	$\bigcirc$	מעט מאוד												
				21	ת פיזי	מרחיו	פעילוח	רמה דרשה ה						
	7	6	5	4	3	2	1							
הרבה מאוד	0	0	0	0	0	0	0	מעט מאוד						
היה קצב הביצוע הנדרש?														
	7	6	5	4	3	2	1							
מהיר מאוד	0	0	0	0	$\bigcirc$	$\bigcirc$	$\bigcirc$	איטי מאוד						
עד כמה הצלחת. מבחינתך, בביצוע פעילות זו?														
	7	6	5	4	3	2	1							
הצחלתי מאוד	$\bigcirc$	0	0	0	0	$\bigcirc$	$\bigcirc$	לא הצלחתי						
האם נדרשת לעבוד קשה בזמן הפעילות? 1														
קואה מאוד	, O	Ô	0	0	0	0	0	בבלל לא						
into rep	0	0	0	0	0	0	0	KI IIJI						
	זו?	פעילות	ז בזמן	וו מרוג	שקט, א	וח, לא	את מתו	עד כמה הרגש						
	7	6	5	4	3	2	1							
מתוח/מרוגז	$\bigcirc$	0	0	$\bigcirc$	0	0	0	בכלל לא						
באיזה מידה הרגשת שהיד על המסך היא היד שלך (מה היתה מידת השליטה ביד המדומה)?														
	7	6	5	4	3	2	1							
הרבה מאוד	0	0	0	$\bigcirc$	0	$\bigcirc$	$\bigcirc$	מעט מאוד						

Figure 17 – Translated NASA TLX

	Table V	- NASA T	LX results
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	WITHOUT ERROR									WITH ERROR											
MENTAL	5	3	4	4	1	3	5	4	4	4	3	2	2	6	6	2	4	3	4	3	2
PHYSICAL	3	5	4	2	1	5	1	4	1	5	3	3	3	5	2	4	2	2	2	2	3
TEMPORAL	4	5	5	5	4	4	4	5	3	6	5	5	3	5	6	5	5	5	6	4	4
PERFORMANCE	6	5	6	5	6	6	6	5	5	4	5	6	6	6	5	5	5	4	5	3	3
EFFORT	2	4	2	2	1	4	5	2	3	4	3	1	1	5	2	3	4	5	4	3	4
FRUSTRATION	1	2	1	1	1	1	1	1	1	5	2	1	1	4	1	1	1	5	1	2	1
LOOK AND FEEL	6	5	7	6	7	4	7	4	5	4	4	4	2	5	6	3	4	3	4	5	3

## Appendix 3 - System development with Unity<sup>TM</sup>

In the begging of the process we used Unity software to develop the interactive game. Unity<sup>TM</sup> (Unity Technologies, California). Unity gives users the ability to create games and experiences in both 2D and 3D, and the engine offers a primary scripting API in C#, for both the Unity editor in the form of plugins, and games themselves, as well as drag and drop functionality. Using Microsoft Kinect package provided by Unity and gave us an avatar and data regarding the joint's locations of the player. We created a game where an aquarium with a fish and food appear on a table. There are 3 locations for the fish and 3 for the food when one is randomly selected at each stage. The game environment appears in figure 17. We tested the accuracy of the elbow angle calculated from the Kinect data. Not surprisingly, we realized that we need to perform corrections on the sensor data, the accuracy check is presented in the next appendix. This led us to change strategy and develop the system using Touch Designer.



Figure 18 - Game environemnt. One fish bowl-food position combinations presented. One of the significant advantages of the Unity software is the very high graphical capabilities. This is not relevant to our system because we wanted to create a simple game to suit the patients reduced capabilities. Conversely, Touch Designer enables calculations to be made rapidly using the GPU. This ability was utilized by application of an extended Kalman filter to the sensor data and also insertion of the error to the elbow joint which worked smoothly with touch designer.

Appendix 3a - System Accuracy

During development, we checked the accuracy of the system regarding elbow angle. In order to test the accuracy of the system we calculated the angle of the elbow joint in different positions of the arm. We then compared the angle as reflected from the system to the angle in reality as measured with a goniometer.

We tested impact on the angle of the joint with three different factors. The first factor was the location of the camera. The second factor was the shoulder angle with two levels and the third factor was the elbow angle with three levels. Hand rests are shown in figure 19.



Figure 19 - description of the shoulder and elbow levels

Overall, we calculated the elbow angle for each subject 18 times. We tested four subjects with different heights for repetitions. We were interested in examining whether any of the factors affect the accuracy of the system. Accordingly, we chose to use the statistical analysis of ANOVA. For each repetition, we calculated the absolute difference between the measurement of the goniometer and the angle we calculated in the Kinect and inserted it as input using software for statistical calculations.

The results were: No main effects seem to influence the mean of the absolute difference. Interactions did not seem significant. We are only interested in the mean of absolute difference. With a probability of 95%, the accuracy of the system for the elbow joint angle is  $(7.73^{\circ}, 11.9^{\circ})$ .

#### תקציר

שבץ מוחי הינו הגורם העיקרי למגבלות מוטוריות ארוכות טווח בתפקוד הגפיים העליונות. עם זאת, הליכי השיקום בגפיים העליונות הנוכחיים אינם מובילים להחלמה מלאה במספר רב של מקרים. במחקר זה, פיתחנו שיטה ומערכת לטיפול חדשני במגבלה מוטורית בגפיים העליונות שנובעות משבץ מוחי. השיטה מבוסס על הוספת שגיאה ברמת המפרקים, ועל תיאוריית בקרה מוטורית. המטרה של אימון זה הינה השגת מיפוי דינאמי מחדש של מנגנוני בקרה ברמת השריר. אנו משערים כי הוספת שגיאה ברמת זווית המפרק תביא לעלייה באזור הבקרה הפעיל של המפרק. ובכך תגדיל את יכולתו של המטופל לבצע תנועה רצונית. המערכת המיישמת את השיטה כוללת שלושה רכיבים: משענת זרוע פסיבית התומכת בזרוע כנגד כוח הכבידה, מערכת עקיבה אחר התנועה באמצעות Kinect ותוכנה המספקת את סביבת העבודה ומשוב חזותי. בעבודה הנוכחית אנו מתמקדים בסביבת המציאות המדומה. המערכת המוצעת דורשת תוכנה אשר בעזרתה ניתן להקרין על המסך יד ווירטואלית הנעה לפי תנועת המטופל, כך שנוכל לבצע עליה הפחתה של 10 מעלות מזווית המפרק. בנוסף לכך, המערכת כוללת סביבת משחק אשר מעודת את השחקן לבצע חזרות על פעולת פשיטה של היד. משימת המשחק הינה הושטת היד אל עבר מטרה כדורית המוצגת במישור אופקי. לפני האימון מבוצע כיול של מרחב העבודה בכדי להבטיח שהמטופל מסוגל להגיע אל המטרות. על המסד מוצגת זרוע וירטואלית מול המטופל, אשר נעה על פי מידע מחיישן הקינקט. לצרכי בחינת המערכת ניתן להפעילה עם, או ללא, שגיאה של 10 מעלות בזווית המרפק. משימת ההושטה מוגבלת בזמן, כאשר ניתן להתאים את הזמן ליכולות המטופל. משוב חיובי חזותי ניתן עבור כל הצלחה בהגעה אל הכדור. עבור מעקב אחר התקדמות המטופל, המערכת שומרת את משך הזמן שלקח למטופל להגיע אל כל מטרה. ניסוי המערכת נערך עם נבדקים בריאים כדי לבדוק האם העומס הקוגניטיבי והתחושה דומים כאשר יש או אין הוספה של שגיאה, והאם רמת הביצועים (משכי ביצוע ואחוזי הצלחה ) דומים. התוצאות התקבלו כפי שציפינו בהתאם להשערה; הנבדקים בקבוצה אשר התאמנה על מערכת עם שגיאה שינו את אופן תנועתם, ללא הבדל בתוצאות המדד הסובייקטיבי. עובדה זו תומכת בכך ששיקום . תנועה באמצעות טיפול בשגיאה ברמת המפרקים היא כיוון מבטיח לשיפור טווח התנועה אצל אנשים שעברו שבץ

מילות מפתח: מציאות מדומה, טיפול באמצעות שגיאה, שבץ, שיקום מוטורי

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אוניברסיטת בן גוריון בנגב הפקולטה למדעי ההנדסה המחלקה להנדסת תעשיה וניהול

מערכת שיקום מוטורי לאחר שבץ המתבסס על טיפול באמצעות שגיאה

חיבור זה מהווה חלק מהדרישות לקבלת תואר מגיסטר בהנדסה

לילי סרור

פרופ' סיגל ברמן

חתימת המחבר:....לילי סרור.... ל'ל' סריר אישור המנחה:....סיגל ברמן..... אישור יו"ר ועדת תואר שני מחלקתית:...לסקרי הקניצי....

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מנחה:

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ספטמבר 2019

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## מערכת אימון מבוססת מציאות מדומה עבור טיפול שיקומי הכולל הוספת שגיאה בנפגעי שבץ

חיבור זה מהווה חלק מהדרישות לקבלת תואר מגיסטר בהנדסה

מאת: לילי סרור

ספטמבר 2019