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Tilt simulation : virtual reality based upper extremity stroke rehabilitation

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ABSTRACT

TILT SIMULATION: VIRTUAL REALITY BASED UPPER EXTREMITY STROKE REHABILITATION

by
Harish Damodaran

The primary objective of this research is to design a recreational rehabilitation videogame that interactively encourages purposeful upper extremity gross motor movements. The simulation is also capable of continuous game modification to fit changing therapy goals, to match the needs of the players, and to provide continued motivation while capturing the interactive repetition. This thesis explains the design and features of this latest simulation - Tilt. Tilt uses physics to develop an engaging training experience and provides a realistic approach to virtual reality simulation including friction, elasticity and collisions between objects. It is designed to train upper extremity function as a unit involving multiple modalities simultaneously, either unilaterally or bilaterally.

It is the latest addition to the NJIT Robot Assisted Virtual Rehabilitation (RAVR) system. It Employs the Cyber Glove and Flock of Birds systems to interface with the real world. This allows training motor function of patients that come to use in day to day life like making use of hands, fingers and shoulders to pick small objects on table, moving them and placing them elsewhere.

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by
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Dedicated to
My Parents Damodaran and Suseela,
My sister Nithya Shree, my nephew Akul,
brother in law Prabhu,
all my friends

&

To the spirit of scientific discovery and countless victims of stroke.

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CHAPTER 1

INTRODUCTION

1.1 Objective

The primary objective of this research is to design a recreational rehabilitation videogame that interactively encourages purposeful upper extremity gross motor movements. The simulation is also capable of continuous game modification to fit changing therapy goals, to match the needs of the players, and to provide continued motivation while capturing interactive repetition. This thesis explains the design and features of the latest simulation - Tilt. Tilt uses physics to develop an engaging training experience and provides a realistic approach to virtual reality simulation including friction, elasticity and collisions between objects. It is designed to train upper extremity function as a unit involving multiple modalities simultaneously, either unilaterally or bilaterally.

To understand the significance of these training measures and benefits of utilizing virtual reality simulations in training, more needs to be understood about stroke and its effects on impairments, neuroplasticity of stroke victims and the current use of virtual reality in stroke rehabilitation.

1.2 Stroke

A stroke (sometimes called a cerebrovascular accident (CVA)) is the rapidly developing loss of brain function(s) due to interruption of the blood supply to the brain. This can be due to ischemia (lack of blood flow) caused by blockage (thrombosis, arterial embolism), or by a hemorrhage (leakage of blood). As a result of a stroke the affected area of the brain is unable to function, leading to inability to move one or more limbs on one side of the body, inability to understand or formulate speech, or inability to see one side of the visual field. [1]

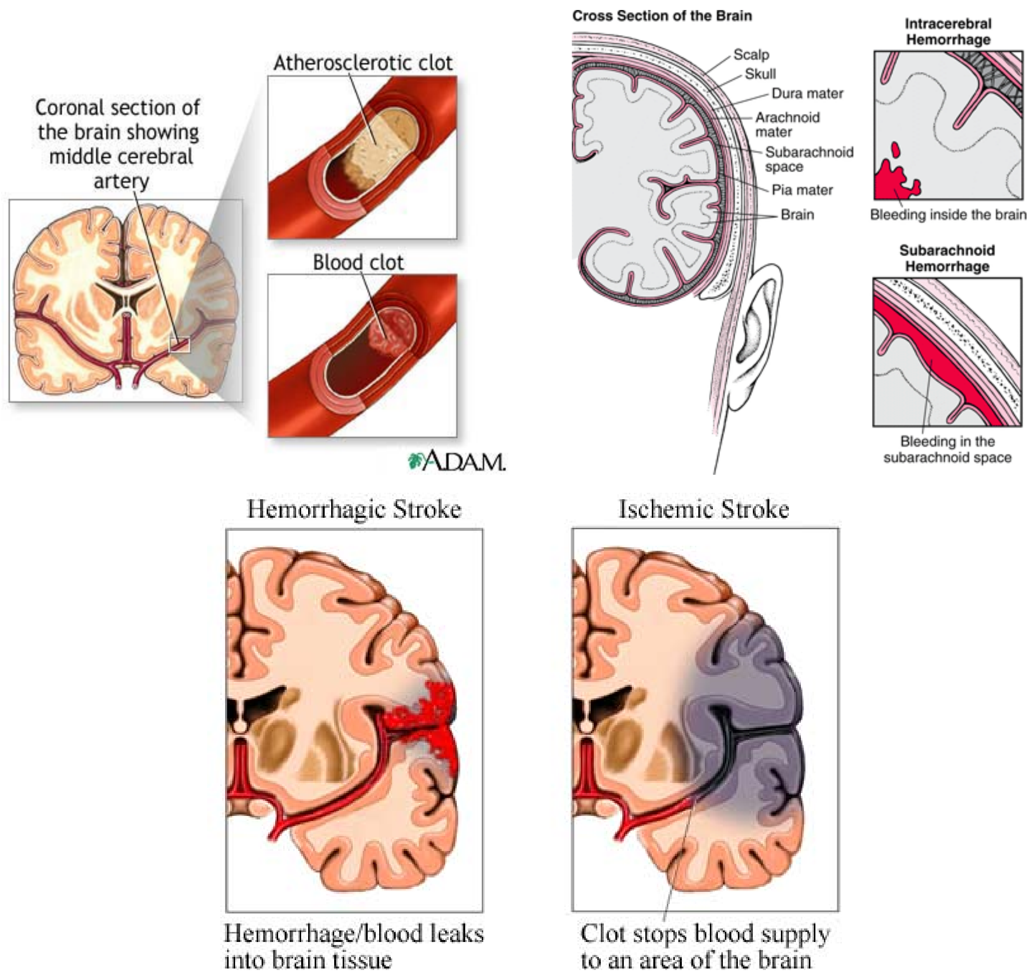

Figure 1.1 Representation of Ischemic stroke and Hemorrhage.
Source: http://dr-lokku.com/docblog/files/2009/09/stroke-2.jpg

Stroke is the second most common cause of death in the United States and it is the third largest cause of death, killing 137,119 people in 2006. About 6,400,000 stroke survivors are alive today; Data from National Institute of Neurological Disorders and Stroke (NINDS) studies show that about 795,000 people suffer a new or recurrent stroke each year. About 610,000 of these are first attacks and 185,000 are recurrent attacks. From 1995 to 2005 the death rate from stroke declined 33.5 percent, and the actual number of stroke deaths declined 18.4 percent [2].

This indicates that the total number of survivors of stroke is on a rise. Since stroke is also the leading cause of adult disability, with 65% of the nearly four million people in the United States who have survived a stroke living with minor to severe impairments [3]. Impairments such as muscle weakness, loss of range of motion, and impaired force generation create deficits in motor control that affect the stroke survivor’s capacity for independent living and economic self-sufficiency. Hence a new and improved form of stroke rehabilitation is important.

1.3 Neuroplasticity in Stroke Victims

The concept of neuroplasticity includes all possible mechanisms of neuronal reorganization, including recruitment of non damaged pathways that are functionally similar to the damaged ones, synaptogenesis, dendritic arborization, and reinforcement of existing but functionally silent synaptic connections. Animal and human studies have shown that important variables in learning and relearning motor skills and in changing neural architecture are the quantity, duration and intensity of training sessions. There is evidence to demonstrate that plasticity is “use-dependent” and intensive massed and repeated practice may be necessary to modify neural organization [4-9] and effect recovery of functional motor skills [10,11]. The importance of intensity and repetition has also been confirmed for stroke patients in the chronic phase in the treatment paradigm referred to as constraint-induced-movement-therapy (CIMT) [5,10]. Use-dependent cortical expansion has been shown up to 6 months after 12-days of CI therapy in people post stroke. In addition to the repetitive and intensive training necessary to induce neural plasticity, sensorimotor stimulation must involve the learning of new motor skills. Evidence strongly emphasizes that learning new motor skills is essential for inducing functional plasticity. Therefore, it appears that critical variables necessary to promote motor changes and neural plasticity are the dynamic and adaptive development and formation of new motor skills. It is believed that adaptive training paradigms that continually and interactively move the motor outcome closer and closer to the targeted skill are important to foster formation of better organized motor skills [14].This change in neural plasticity can be brought about by the use of virtual reality in rehabilitative training.

1.4 Virtual Reality and Robots in Stroke Rehabilitation

Virtual Reality (VR) can be defined as an approach to user-computer interface that involves real-time simulation of an environment, scenario or activity that allows for user interaction via multiple sensory channels. Virtual environments in virtual reality systems can be used to present rich and complex multimodal sensory information to the user that can elicit a substantial feeling of realness. [15, 16]

Visual stimuli are grouped by the level of immersion. Fully immersive system systems allow for changing visual perspective with head movement for example the Cave Automatic Virtual Environment (CAVE). Three dimensional presentations utilizing stereoscopic projections or displays with a fixed visual perspective are considered semi-immersive. Two-dimensional presentations that make use of a computer display are considered non-immersive. Rehabilitation using virtual reality is currently utilizes two-dimensional presentations and three dimensional stereoscopic projections as they bring about maximum desired effect of training.

In the real world, knowledge about the environment is gained directly through the senses; vision, hearing, touch, proprioception, smell. In the virtual world, the same senses are utilized to obtain information about the virtual world through a human–machine interface (e.g., head-mounted visual display). The human machine interface can provide information specific to one or more senses, depending on the type of devices that have been selected for use. The information gathered about the virtual environment through the interface is then used to guide interactions of the participant within the virtual world. Input from the virtual environment can also be combined with natural sensory inputs from the real environment, to create a hybrid input to the central nervous system (CNS).

Figure 1.2 Commercially available VR system IREX.

Use of VR as a training environment may provide a rehabilitation tool that can be used to exploit the nervous systems’ capacity for sensorimotor adaptation by providing a technological method for individualized, intensive and repetitive training. In addition to the training intensity and volume necessary to induce neural plasticity, sensorimotor stimulation would involve the learning of new motor skills. Computerized systems are well suited to this and afford great precision in automatically adapting target difficulty based on individual subject's ongoing performance. When virtual reality simulations are interfaced with movement tracking and sensing glove systems they provide an engaging, motivating and adaptable environment where the motion of the limb displayed in the virtual world is a replication of the motion produced in the real world by the subject.[17]

Evidence suggests that sensorimotor training in VR may actually have similar effects to those noted after real-world training. This evidence comes from several domains. First, studies that have compared the kinematics of movements performed during interaction in a virtual visual environment to those when acting in the real world have found remarkable similarities. For example, healthy subjects responding to targets moving at different velocities exhibit similar movement time, path curvature time, time to peak velocity, and reactions times whether the task is performed in a VE or in the real world [18, 19]. Interestingly, stroke patients' kinematics for reach–to-grasp movements also show similarities in peak wrist velocity, angular shoulder/elbow relationship and maximum grip aperture when acting in the virtual versus a real environment [20].

The advantage of using VR in community, clinical and laboratory settings is that by virtue of its programmability, environments and the amount and type of feedback can be modified according to the user's motor capacities, motivation and therapeutic goals [21]. In addition, sensory parameters of the environment can be creatively adapted to evoke responses to a larger number of situations in a shorter amount of time than is available in physical set-ups. VR based applications can provide adaptive learning algorithms and graded rehabilitation activities. These can be methodically manipulated to interactively move the subject's performance towards a targeted skill [22] which is important to optimize re-learning of motor skills [14].

The New Jersey Institute of Technology Robot Assisted Virtual Rehabilitation (NJIT-RAVR) system consists of engaging virtual environments and simulations which include the above mentioned attributes of a VR system. Chapter two mentions in detail the various components of this system and their specialized training hardware. Chapter 3 explains in detail the design and features of the latest addition to this system- Tilt game simulation.

CHAPTER 2

NJIT RAVR SYSTEM

Many traditional therapeutic interventions have been used in rehabilitation to promote functional recovery with outcome studies yielding varied and inconsistent results with the use of virtual reality, repetitive training can be provided to affected parts with an engaging environment. This intensive and repetitive training method has been shown to be effective in promoting cortical plasticity and behavioral recovery [23].

The following chapter describes the New Jersey Institute of Technology Robot Assisted Virtual Rehabilitation (NJIT RAVR) system [24, 25]. The following will be described; 1) the hardware required to connect the user with the virtual world, 2) the different simulations currently available as part of the NJIT RAVR library of simulations, 3) the kinematic measures available with the system.

2.1 Hardware

Different commercially available hardware is used to connect the user with the virtual world. Depending on the measurements to be made and user experience required, one of the following systems is chosen in the NJIT- RAVR system.

2.1.1 Flock of Birds

Flock of Birds manufactured by Ascension technology (Burlington, Vermont) is a pulsed DC magnetic technology that can measure six degrees of freedom. Flock of Birds is used to measure the position and orientation of the users hand in the real world three dimensional space in the NJIT-RAVR system. The sensor is attached to the wrist of the user, the X, Y and Z values of the sensor determine the position of the hand with respect to the Flock of Birds transmitter. The pitch, roll and yaw would then determine the angle and orientation of the user's wrist in the virtual environment [25, 26].

The Flock of Birds communicates with the virtual environment using the Virtual Reality Peripheral Network (VRPN)[27]. VRPN is an open source technology that helps in interfacing VR peripherals like the Flock of Birds and CyberGlove to the virtual world.

Figure 2.1 Flock of Birds.

2.1.2 TrackSTAR

Trackstar uses the same principle as Flock of Birds. However, the trackstar sensors are faster and smaller. Rates up to 420 times a second can be chosen for use on up to four sensors at once without daisy chains. They work with the midrange or short range transmitters used with Flock of Birds [25]. In the NJIT-RAVR system they are used to make measurements of the entire arm movements by placing sensors at the wrist, elbow, shoulder and chest.

Figure 2.2 trackSTAR tracking system.

2.1.3 CyberGlove

The CyberGlove motion capture data glove is a high accuracy device capable of measuring 22 joint angles, the total number on a human hand. It uses proprietary resistive bend sensing technology that transforms hand and finger motions into real time digital joint angle data to be used in the virtual environment [27]. The Cyberglove is used in all the NJIT-RAVR simulations that involve finger training.

Figure 2.3 CyberGlove from Ascension Technology Corporation.

2.1.4 CyberGrasp

The CyberGrasp also manufactured by Ascension Technology Corporation is an innovative force feedback system for fingers and hand. The CyberGrasp is a lightweight force –reflecting exoskeleton that fits over a CyberGlove data glove and adds resistive force feedback to each finger. The CyberGrasp is used to train subjects who need assistance with individual finger movement by resisting flexion of the adjacent fingers[27].

Figure 2.4 CyberGrasp System from Ascension Technology Corporation.

2.1.5 Haptic Master

The Haptic Master (Moog FCS Corporation, Ann Arbor, Michigan) is a 3 degrees of freedom, admittance controlled (force controlled) robot. Three more degrees of freedom (yaw, pitch and roll) can be added to the arm by using a gimbal with force feedback available for pronation/ supination (roll). A three- dimensional force sensor measures the external force exerted by the user on the robot. In addition, the velocity and position of the robot's endpoint are measured. These variables are used in real time to generate reactive motion based on the properties of the virtual haptic environment in the vicinity of the current location of the robots endpoint [28, 29].

Figure 2.5 Haptic Master.

2.2 Simulations

The NJIT-RAVR system is a unique real time adaptive exercise system that provides guidance for arm movement in three dimensional space using complex visual, auditory and haptic simulations. The following section explains the working of various existing simulations part of the NJIT RAVR library, it makes use of the hardware mentioned in section 2.1 to train the hand and arm separately or the hand and arm together (HAS vs HAT paradigm. [30])

2.2.1 Virtual Piano Trainer

The piano trainer [13] is designed to help improve the ability of subjects to individually move each finger in isolation (fractionation). It consists of a complete virtual piano that plays the appropriate notes as they are pressed by the virtual fingers (Figure 2.6). The position and orientation of both hands as well as the flexion and abduction of the fingers are recorded in real time and translated into 3D movement of the virtual hands shown on the screen in a first person perspective using Cyberglove and the Flock of Birds. The simulation can be utilized for training the hand alone to improve individuated finger movement (fractionation), or the hand and the arm together to improve the arm trajectory as along with finger motion. This is achieved by manipulating the octaves on which the songs are played. These tasks can be done unilaterally or bilaterally. The subjects play short recognizable songs, scales, and random notes. Color-coding between the virtual fingers and piano keys serve as cues as to which notes are to be played. The activity can be made more challenging by changing the fractionation angles required for successful key pressing. When playing the songs bilaterally, the notes are key-matched. When playing the scales and the random notes bilaterally, the fingers of both hands are either key matched or finger matched. Knowledge of results and knowledge of performance is provided with visual and auditory feedback. [28]

Figure 2.6 Virtual Piano Trainer.

2.2.2 Hummingbird Hunt

This simulation depicts a hummingbird as it moves through an environment filled with trees, flowers and a river. Water and bird sounds provide a pleasant encouraging environment in which to practice repeated arm and hand movements (Figure 2.7). The game provides training in the integration of hand reach, hand-shaping and grasp using a pincer grip to catch and release the bird while it is perched on different objects located on different levels and sections of the workspace. The flight path of the bird is programmed into three different levels, low, medium and high allowing for progression in the range of motion required to successfully transport the arm to catch the bird. Adjusting the target position, as well as the size scales the difficulty of the task and the precision required for a successful grasp and release (Meriams 2008).

Figure 2.7 Hummingbird hunt.

2.2.3 Plasma Pong

This is a modified ping pong game. During simulation, a vertical invisible virtual cylinder was created by Haptic Master to allow participants freely move up and down to control the virtual paddle, while restrict the movement forward and backward at the same time. The stream of fluid shooting out of the paddle is controlled by finger extension. Each fluid shooting lasts 5 seconds, and the participants have to close the hand and reopen it to initiate another fluid shooting. How much the fingers have to extent to shoot the fluid is adjustable to each individual. [20]

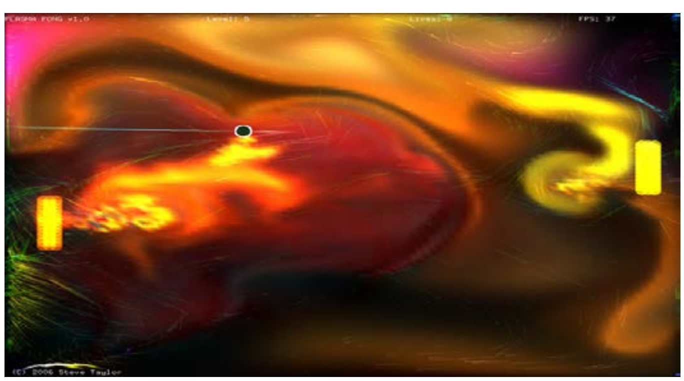

Figure 2.8 Plasma Pong.

2.2.4 Placing Cups

The goal of the “Placing Cups” task is to improve upper extremity range and smoothness of motion in the context of a functional reaching movement. The screen displays a three-dimensional room with a haptically rendered table and shelves (Figure 2.9). The participants use their virtual hand (hemiparetic side) to lift the virtual cups and place them onto one of nine spots on one of three shelves. Target spots on the shelves (represented by red squares) are presented randomly for each trial. To accommodate patients with varying degrees of impairments, there are several haptic effects that can be applied to this simulation; gravity and antigravity forces can be applied to the cups, global damping can be provided for dynamic stability and to facilitate smoother movement patterns, and the three dimensions of the workspace can be calibrated to increase the range of motion required for successful completion of the task. The intensity of these effects can be modified to challenge the patients as they improve. [20]

Figure 2.9 Placing Cups.

VRPN is used to simultaneously read data from 2 sets of Flock of Birds and Cyber Glove via serial ports. The position and orientation of both hands as well as the fractionation of the fingers are recorded in real time and translated into 3D movement of the virtual hand.

2.3 Measurements

Several kinematic measures are derived from the training simulations. Each task in a simulation consists of a series of movements e.g. pressing a series of piano keys to complete a song, or placing 9 cups on the virtual shelves. Time to complete a task, range of motion and peak velocity for each individual movement will be measured in each simulation. In the virtual piano trainer , accuracy, which denotes the proportion of correct key, presses, and fractionation are measures specific to the hand. Peak fractionation score quantifies the ability to isolate each finger's motion and is calculated online by subtracting the mean of the metacarpophalangeal and proximal interphalangeal joint angles of the most flexed non-active finger from the mean angle of the active finger.

When the actual fractionation score becomes greater than the target score during the trial, a successful key press will take place (assuming the subject's active finger was over the correct piano key). The target fractionation score starts at 0 at the beginning of each finger. After each trial, and for each finger, the algorithm averages the fractionation achieved when the piano key is pressed. If the average fractionation score is greater than 90% of the target, the target fractionation will increase by 0.005 radians. If the average fractionation is less than 75% of the target, the target will decrease by the same amount. Otherwise, the target will remain the same. To calculate movement smoothness, the normalized integrated jerk is computed TNSRE [29] [30] . Finally, in training involving the Haptic Master active force denotes the mean force applied by the subject to move the robot to the target during the movement.

CHAPTER 3

TILT SIMULATION DESIGN

Simulations explained in chapter 2 dealt with training individual components of the upper extremity. Research shows that neural control mechanisms of arm transport and hand object interaction are interdependent [33]. Recognizing the need for training using functionally complex movements the Tilt simulation has been designed to engage the upper extremity as a single unit. Initial findings with the NJIT RAVR system training hand and arm together has shown greater advantage for improving functional activities over training them separately [28, 35].

This chapter explains the latest addition to the NJIT RAVR system, the Tilt simulation, which explores this paradigm through design and game play. It explains the objectives that are fulfilled in its design, designing the game through Virtools, and various algorithms that control and have been incorporated to arrive at a visually engaging and realistic training simulation designed to provide faster transfer of VR training into real world.

3.1 Using Virtools

The Tilt simulation was designed in Virtools. Before understanding the design objectives and working of the system its necessary to understand basics of the software package used to build the system. Some of the features more relevant to certain aspects of game design are explained in later sections where necessary.

Virtools is an extensive collection of technologies for 3D visualization and interactivity. The Virtools technologies can be broadly classified as a collection of the following components.

1. An Authoring application
2. A Behavioral Engine
3. A Render Engine
4. Web Player
5. A Software Development Kit (SDK)

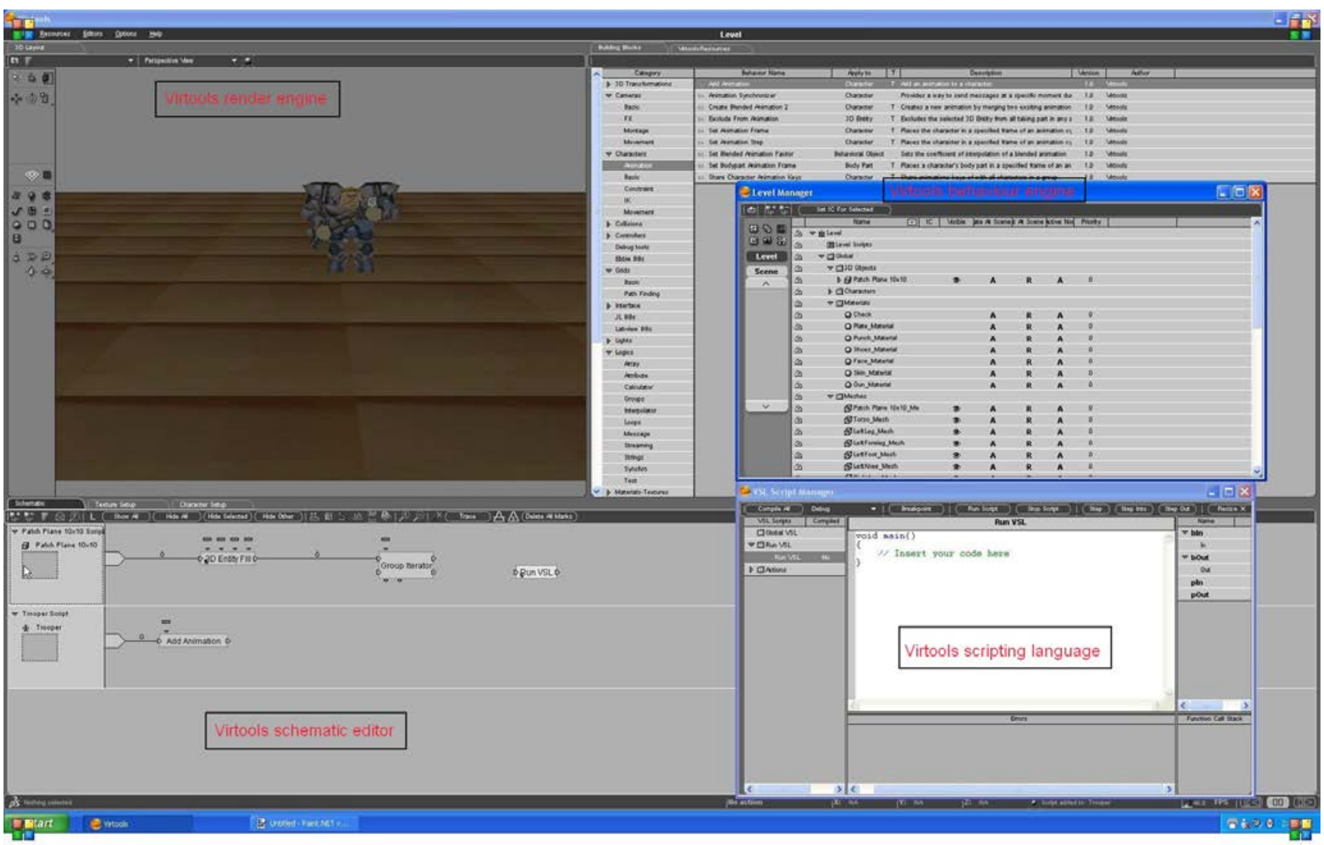

Figure3.1 Virtools user interface.

The Virtools interface can be seen in Figure 3.1 The top left window of the screen represent the render engine. The render engine in Virtools is responsible for drawing different objects, characters and components in 3D layout as seen by the user during the running of the simulation.

The Virtools schematic editor below the render engine is part of the Virtools behavior engine. Its function is to define the behavior of one object with the other in the virtual environment. Virtools behavior engine provides an extensive collection of reusable behaviors (Building Blocks) in Virtools that allow creation of almost any type of content through the simple, graphical interface of the schematic editor.

Virtools Scripting Language (VSL) complements the Virtools schematic editor by providing script level access to the Virtools Software Development Kit (SDK). Virtools also has a number of managers that help the behavioral engine perform its duties. Some of these managers (such as the TimeManager) are an internal part of the behavioral engine while others (such as the SoundManager) are external to the behavioral engine.

Virtools as an authoring application allows quick and easy creation of rich, interactive, 3D content. Standard media such as models, animations, images and sounds are brought to life by Virtools' behavior technologies. Models cannot be created in Virtools; Virtools is not a modeling application. However, simple media such as cameras, lights, curves, interface elements, and 3D frames (called dummies or helpers in most 3D modeling applications) can be created with ease.

Virtools includes a Software Development Kit (SDK) that provides access to certain parts of the behavior and rendering processes. With the SDK, new behaviors can be created (DLLs), modify the operation of existing behaviors, write new file importers or export plug-ins, to support the modeling file format of choice

3.2 Objectives of Game Design

The simulations currently used in the NJIT-RAVR system when considered, each of these simulations serves well to train one component of the upper extremity individually and used together train in the complete upper extremity. For example, virtual piano trains individual finger fractionation, humming bird hunt trains reach and grasp and cups trains shoulder articulations and arm extension. During training, it is important to train both the proximal and distal components of the upper extremity in conjunction with one another [35].

The first goal of the Tilt simulation is to explore the benefits of training the upper extremity as a whole. This training would involve movement of elbow and shoulder including abduction, extension and pronation of the arm to reach objects placed on various tables across the virtual environment, and finger motion necessary for grasping objects of different sizes and shapes. This would also help in enhancing the active and passive range of motion and hand eye coordination, and might utilize bilateral movements guided by the less impaired upper extremity.

The secondary objective of this design is to provide a training experience that could be more closely associated with everyday activities. For example, on a daily basis most of us are involved with manipulating various objects on a desk or a table. This similarity is brought about in the simulation by adding four tables with various objects scattered across each of the tables. The objects are also similar to the shapes and sizes that a person would be involved with, e.g., cylinders, cubes of varying dimensions and varying shapes. The rehabilitation aspect of this design would be the task of reaching for objects (shoulder and arm movement), use of fingers to manipulate grasping and releasing objects of varying sizes and shapes while responding to the visual cue of where to place the objects. Interacting with objects at different heights and varying distances away from each other might help in recovering shoulder function.

The ability to visualize a representation of one's own hand moving through the virtual spaces may strengthen a participant's feeling of being involved in an action and of attributing that action to themselves. This appears to be related to the degree of concordance between the intent of the movement, the participant's kinesthetic experience and the sensory feedback provided by the virtual environment [34].

3.3 Tilt VS NJIT RAVR System

The Tilt simulation is an addition to the current library of NJIT RAVR simulations. It henceforth utilizes components of the current system in interfacing with the real world. The Tilt simulation makes use of the CyberGlove to measure joint angles and finger fractanations and the Flock of Birds system is connected to the wrist of the user to determine the position of the hand and to move the virtual hand within the simulation. The current system when connected with the four sensors of the Trackstar is capable of measuring the movement of the entire upper extremity.

The current system does not provide any haptic feedback. The user connects to the virtual world using the VRPN through the CyberGlove and Flock of Birds. It differs from the existing system in its training capabilities. It can train the shoulder movement and arm reach and grasp movements along with grasping task simultaneously. The NJIT system on the other hand is capable of similar training over the two week training period by utilizing multiple simulations. Figure 3.2 explains the simulations and the corresponding hardware they use with the resulting training they produce.

The Tilt simulation is capable of producing the same measurements as the combination of two or more of the current NJIT RAVR systems.

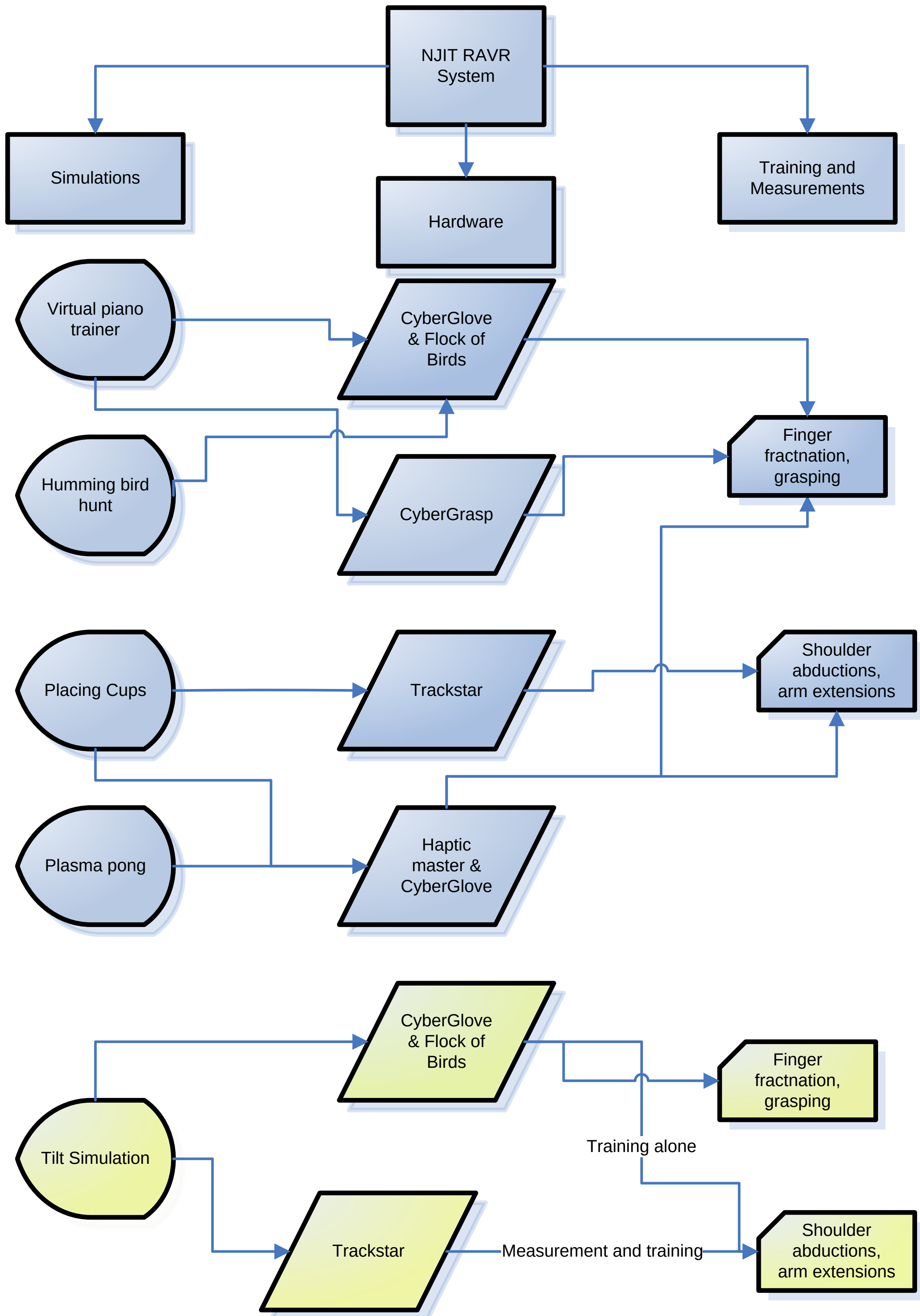

Figure 3.2 Differentiating the Tilt Simulation with the current NJIT RAVR system.

3.4 Having Fun: Playing the Tilt Simulation

It is important to understand how Tilt Simulation works before getting into the design details of the virtual world, and various algorithms controlling them. . The main objective of the Tilt simulation is to manipulate the direction of the ball from its starting position and direct it toward the end goal position. This task is to be achieved by using objects from tables around the center table to direct or divert the direction of the ball.

To start playing the simulation the user first needs to calibrate the CyberGlove for the size of their hand. The CyberGlove is commercially available in standard sizes but the location of individual joints on the fingers vary from user to user and between healthy and stroke subjects. The calibration program used is a standard calibration program part of the existing RAVR system. It is used for other RAVR systems that involve the use of CyberGlove. The standard procedure of calibration involves placing the hand in the following orientations. 1) All fingers flat on a surface, 2) make a fist with all joints at 90 degrees, 3) extend fingers with 20 degree abductions between them, 4) touch the thumb to each of the other fingers, 5) make an angle of 45 degrees with wrist, 6) make 20 degree abduction with wrist, 7) place all fingers flat with thumb 90 degree to the other four fingers. At the end of these steps a calibrated hand model is seen on the screen doing the same movements as the user.

To begin the game set initial conditions (in Virtools) and hit play. With the start of the game press “R” key on the keyboard to reset the position of the final position of the ball. Once the position is set the ball begins to move towards the final position frame (not visible to the user, say position C on Table A) the user now takes active part in the game by picking any of the object (E) from one of the side tables (Table B)(Figure 3.3). The user needs to grasp one of these objects from the side table and place it on the Table A. The objects need to placed relative to the position of the ball such that ball would collide with the object. The collision between the ball and the object used would cause the direction and the force on the ball to change. The user now needs to use another or multiple objects from the side tables (B on Figure 3.3) to direct the ball towards the position D on the center table. When the ball reaches the goal (position D) one trial is said to be complete and the user scores one point.

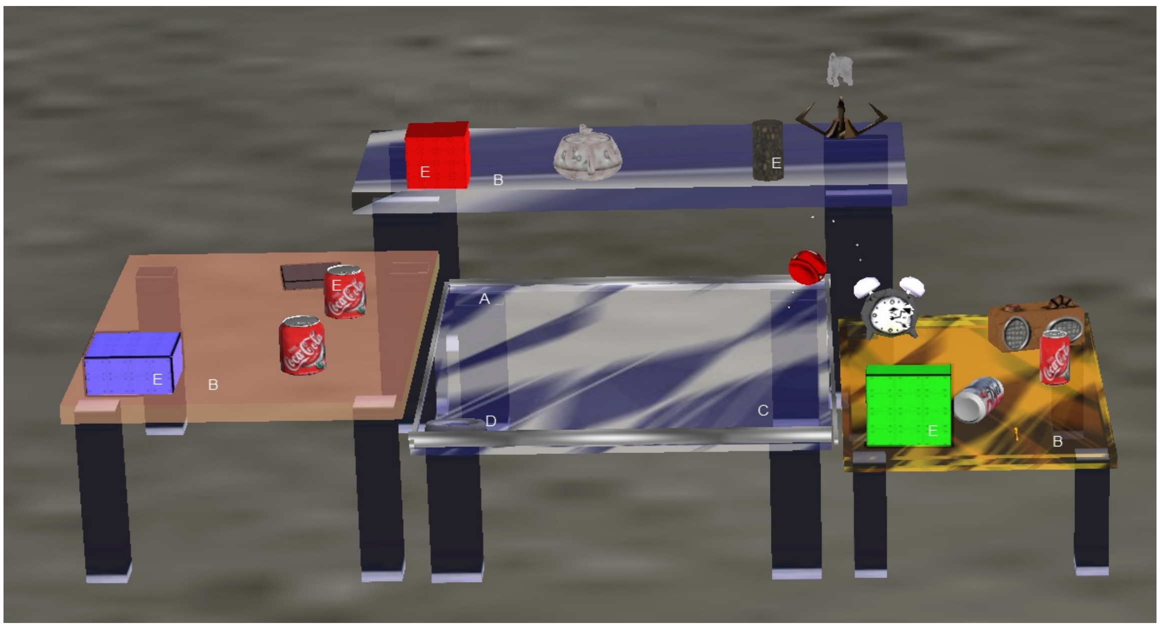

Figure 3.3 Tilt Simulation.

At the end of one trial the objects and the ball positions are reset. Pressing “R” would begin a new trial.

CHAPTER 4

UNDERSTANDING THE DESIGN

All virtual simulations run on specific algorithms. The desired output of any virtual environment is encoded within its design and algorithm. Modern day video games and simulations also have set of algorithms working together to provide the user with the desired experience, these are known as game engines. On similar lines the design of the Tilt game engine can be explained as a part of two sets of algorithms/engines.

First is the physics engine, that uses principles of physics in the objects and the virtual world to provide a more realistic experience to the interactions happening within the virtual world. Second is the set of algorithms that functions to integrate the physics components with other components that define game experience, namely audio, video, camera position and orientation, scores, time, game start and reset, etc. The following section helps in understanding the various components of the physics engine.

4.1 Physics in Virtual Environment

The Tilt simulation was programmed in Virtools. Virtools does not allow complete modeling of an object, but it allows design of basic shapes and modifications such as textures, colours and overall size and shape. The objects designed in Tilt simulation were either imported models (like soda cans, USB, etc) designed in 3DMax, Maya and other design softwares or were modelled over basic shapes and models available within the Virtools resource directory (like the table, cubes, ball, etc).

Design using the inbuilt Virtools resource is fairly simple. For example the cubes were designed based on one of the standard designs called patch. A cube ‘patch’ was chosen and imported into the render engine. The size, shape and location in the virtual world were then modified. The textures, colors required were then chosen and inserted to the patch. Any required lighting can be then provided. Now the cube is ready for scripts or algorithms that would decide on its behavior.

4.1.1 Fixed Objects and Constant Objects

A modern day virtual simulation can be defined as a complex assimilation of visual cues. For example, when a car racing game is considered, there are various aspects on the screen at any given point that keep changing. There is the car which keeps moving on a track, the world around the track, buildings and surroundings around them that keep changing simultaneously, a speedometer which responds to the user commands and a few other drastic changes in the event of a car crash or changes according to the story line.

When this complex virtual environment is broken down into various components, it can be seen that some do not change over time. The track in the above example is predesigned and does not change dynamically. These components can be considered as game constants. The Tilt simulation is a much simpler simulation compared to the above example. It is made of a floor with four tables of varying heights and dimensions arranged in a specific fashion. The tables and floor constitute the fixed objects/ game constants within the Tilt simulation. They have a fixed dimension and their position and properties are fixed during the run. Each of these tables and the floor has physics properties similar to the real world floor and tables. All the tables have the same amount of friction and elasticity but different textures for visual appeal. They vary in height as well.

In Figure 4.1 Table a is the farthest away from the user and also the highest amongst the four. The distance helps in reaching out for extension of the shoulder, while the height helps shoulder flexion. Table b and table d on either side of table c are taller and shorter respectively to the center table (table c). They encourage extension and abduction of the shoulders. At the center table c where most of the interaction takes place, it requires manipulation of objects picked from other surrounding tables. This encourages finger fractionation and practice of grasp and release. Hence a single run of the simulation would allow the training of complete upper extremity.

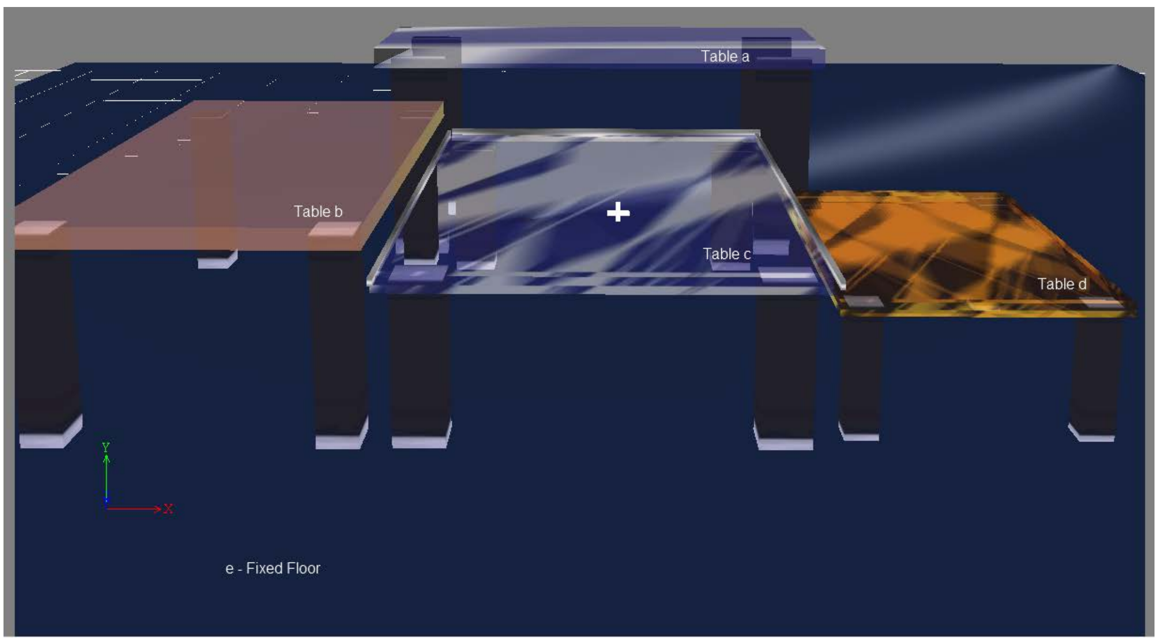

Figure 4.1 Fixed objects: The virtual environment fixed objects is made up of four tables- tables a, b, c, d on the fixed floor(e). The varying heights and distances of the tables from the user can be observed.

Other game constants of this simulation are objects that are present during the entire course of the game and have fixed physics properties, but unlike the fixed objects they can be moved around. These include objects that are used for playing the game, objects of varying dimensions and shapes such as coke cans, a radio, clock, cubes and other cylindrical objects.

Each of these objects have different elasticity, friction and mass but these properties are fixed during the run. The friction and elasticity of these objects is described in table 4.1. The friction and elasticity of various cubes and cans are determined by a factor of their size.

Figure 4.2 Movable objects of different dimensions placed on one of the side tables.

The friction and elasticity described in Table 4.1 gives the value of the smallest size, the base value. The values are assigned to the smallest cube or cylinder in the virtual world. The value of the other cube or cylinders can be calculated by multiplying it with a factor of their mass.

Table 4.1 Friction and Elasticity of Various Objects in the Virtual Environment

Object Units	**Friction** Units	**Elasticity** Units
Cube 1	2.20	2.9
Coke Can 1	0.70	6.2
Pen Stand	0.25	13.2
Clock	0.11	28.5
Radio	0.05	62.0

4.1.2 Physics of the Ball

The Tilt simulation is based on the control and manipulation of the ball on the center table. This control however is not achieved by manipulating the ball directly; the user controls the movement of the ball by using the objects mentioned in table 4.1. The user picks these objects from their current position and places it in the path of the ball, the physical properties of the ball then take over to define speed and direction of the ball movement.

The ball has a mass of 10 units and a friction coefficient of 1.5 units and an elasticity coefficient of 2 units. These properties make the ball bounce off certain surfaces more than others. The choice of the object would determine the course of the ball based on the elasticity and mass of each of the objects selected. The deflection and direction of movement is based on the orientation of the object.

At the start of the game the ball end position can be reset by pressing "R" key on the keyboard. This would activate the randomization algorithm (section 4.2.1) and provide a new end position for the ball. The direction and motion of the ball towards this target is controlled by a *Motion Controller* Building Block (BB). This BB controls a physical object by making it home towards another 3D entity. In this case the ball is given force to home towards the dummy frame (end position frame) that determines the end position of the ball on the center table. This building block provides a constant force for the ball to move towards the end position frame. The maximum translation force and rotational force in individual axis can be set before the start of the trial. These determine the speed and spin on the ball.

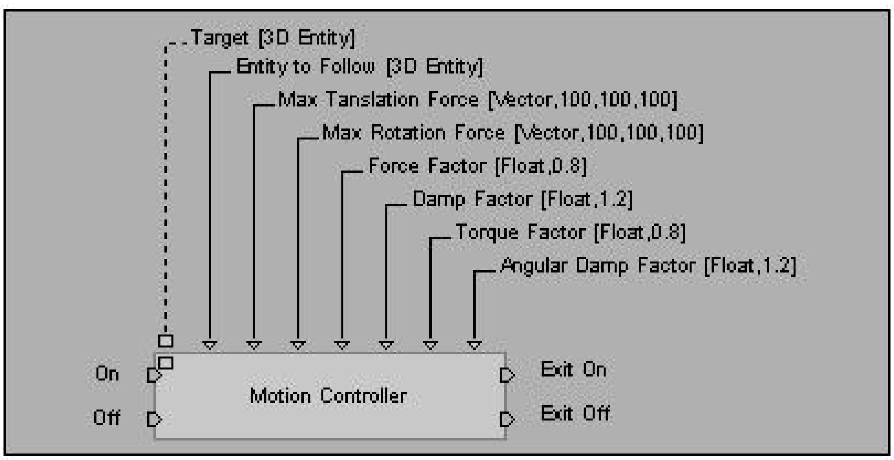

Figure 4.3 Motion Controller Building Block.

When the ball comes in contact with any obstacle placed in its path the properties of physics acts upon the ball, hence changing its course towards the desired destination. The end position is a frame created to designate manually the end position for the ball on the table (Figure 3.5).

4.2 Game Algorithms

The previous section explained the components of the physics engine. But for a game/ virtual simulation to be successful in its design or therapeutic goals, the experience provided by the physics engine, as well as other components like audio, visual, performance scores and time are important. This section gives an overview of some of the important algorithms used in Tilt simulation that help in creating the game experience.

4.2.1 Randomization Proximity and Reset

End position is a randomized position on the center table which is used by the motion controller BB to initiate a trial. The movement goal is a position on the lower left edge of the center table which is a fixed target for the user. The user has to direct the ball towards this target to end the trial.

Randomization BB generates a random position vector within the area (Figure 4.4) covering the lower half of the center table. This position vector is used to determine the location of the end position frame which is necessary to trigger the motion controller BB that sets the course of the ball at the start of the trial.

The proximity algorithm calculates the distance of the center of the ball from the frame at the goal position. The distances are calculated between the volumetric centers of the objects. The value of the distances in the horizontal plane is compared to the threshold distance. When the distance is lower than the threshold the *In Range* output is activated triggering the reset algorithm. When the distances are greater than the threshold distance the *Out Range* is activated triggering the proximity BB in a loop.

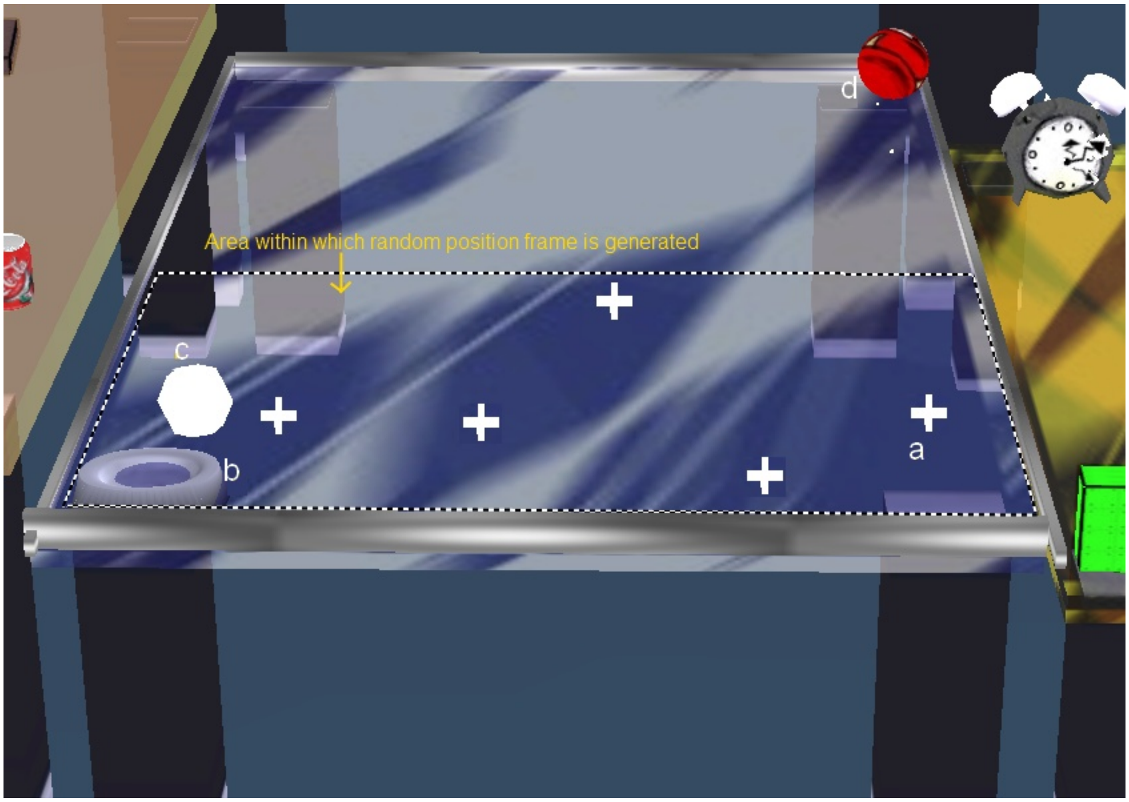

Figure 4.4 End position frame VS Goal. (a) random position frames ; (b) Goal; (c) Frame that represents position of the goal; (d) Initial position of the ball.

The accuracy of the ball reaching the goal can be controlled by the proximity BB. When the threshold distance is large, the *In Range* is activated when the distance between the objects is large implying the ball has not reached the goal. Likewise, when the distance is small it implies the ball has almost reached the goal. Hence the accuracy required from the user can be controlled during training by varying the threshold distance.

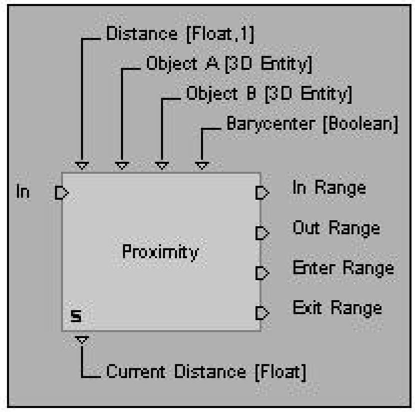

Figure 4.5 Proximity Building Block.

The Reset algorithm controls the initial conditions of the trial. When activated, it resets the position of the ball and all the objects to the position at the start of the trial. This signifies the end of the trial triggering the scorecard and time algorithm to measure the time and record the score to be displayed on the screen. It also resets the camera back to its position at the start of the trial.

4.2.2 Scorecard and Time

The scorecard and time algorithms measure the total time from the start of the trial until the ball reaches the goal. The total number of times the goal is reached is measured as a score. Both the score and the time are measured and displayed on a two dimensional frame on the top right side of the display. The score and time are meant to bring a sense of time and help in motivating the user to get a higher score in less time. The time displayed could be the total time taken to finish a trial or can also be modified to show the total time left in the current trial, based on the requirements of the therapist. The scorecard algorithm is triggered by the proximity algorithm when the object reaches the goal.

4.2.3 Grasping and Picking Objects

This simulation requires its users to pick objects and place it at different locations. The individual fingers and hand movement data is collected simultaneously and transferred to the virtual world. A pair of CyberGloves is used for finger tracking and Flock of Birds gives the position and orientation of the wrist. While the position and orientation of the hand and fingers can be determined in the virtual world, the actual grasping of objects in the virtual world is possible only when forces are applied opposing those already present (for instance, gravity). The CyberGlove or the Flock of Birds does not measure the actual force applied by the user. Since the forces are not transferred to the virtual world, alternate methods to apply forces are required to pick objects.

The grasping and picking algorithm along with the '*Object Picker*' VSL script helps in applying forces in the virtual world to grasp and pick objects. Refer to Appendix A and B for the VSL script and algorithm, respectively. This algorithm makes use of multiple Collision detection BB's to detect the collision between two 3D objects. Every finger is assigned an '*END object*'. The collision between the END object and any 3D object in the virtual world is detected by the collision detection BB. The collision detection BB's connected in series activates the object picker VSL script. This script checks the objects colliding with individual fingers/ finger 'END objects'. When all the fingers collide with the same object the output of the 'Object Picker' block is activated triggering the subsequent object to be picked. This triggers the object as '*pickable*' and the object is connected to the END object of the hand.

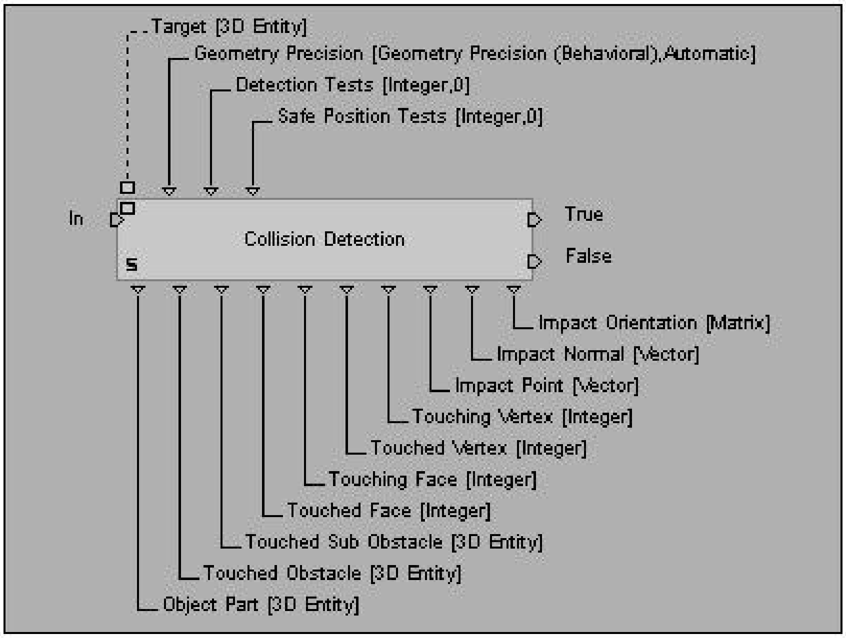

Figure 4.6 Collision Detection.

When any one of the finger stops touching an object, the collision between the END object of the finger and the object is deactivated and hence the input to the script is discontinuous hence deactivating the object from a 'pickable' state causing the object to be dropped due to gravity. The object can be picked from its current position if required by the above principle with all fingers grasping the same object.

4.3 Tilt Game Adaptability

The adaptability of any virtual reality simulation determines its successful use with stroke patients with varied needs. The control of difficulty is necessary to make the training challenging but not too frustrating, because the goal is to make stroke subjects work consistently and successfully over the training period. The Tilt simulation is highly adaptable in the following ways. A change in various physics properties could make a meaningful difference in the game play.

The amount of friction, elasticity and force acting upon the ball would make it move faster or slower, hence increasing or reducing the speed of the ball and the game. A faster ball gives lesser time for making decisions and also difficult to control its direction. Depending on the need of the user, the amount of friction and elasticity of both the table and the ball can be either increased or decreased causing a major change in speed. Finally, a change in the elasticity of the game constants (objects) would change the amount of deflection of the ball off its surface and hence the amount of dynamics within the game; a surface with much less elasticity would cause only a very small deflection off its surface, setting the ball marginally off its path towards the end position frame and vice versa for a surface with high elasticity. This would affect the number of objects required to change the direction of the ball.

A change in the force factor in the motion controller BB would also change the initial force available for the ball and the speed at which the ball approaches the end position frame. An increase in the time to reach means, more time for the user to manipulate the path of the ball. This flexibility in the physical parameters allows the Tilt simulation to be used by a group of stroke patients with varying motor abilities, from very limited to less impaired, or those with slow or fast motor movements.

The accuracy required by the user during training can also be modified by changing parameters in the proximity BB. A higher range would allow the reset algorithm to be triggered sooner, with the actual position of the ball much farther from the goal compared to a very low range, which would require the user to concentrate more on the fine motor movements and accurate placement of objects.

CHAPTER 5

TESTING AND VALIDATION

To show the effectiveness of the system, two independent tests were performed. The first test was to understand whether the design goals were achieved and whether the subjects could perform the game. Volunteers with impaired movements were asked to use the system for a period of 15 minutes and were asked to answer a questionnaire relating to their training. The second study was to compare the subject's behavior to established training measures and movements in the real world. Healthy volunteers were asked to perform upper extremity tasks in the virtual world as well as in the real world and kinematic data were analyzed to prove the efficiency of the game design to elicit real world movements in the virtual world.

5.1 Questionnaire Results

The Tilt simulation was tested by three volunteers who were undergoing rehabilitation after stroke. Their mean age was 53 years and they had suffered a stroke between 5- 7 years ago. Two of the volunteers were male and one was female. All volunteers received verbal instructions about the working of the system and the objective of the game and how to work the system. They were asked to test the system for its design, efficiency and level of difficulty to use. Each of them used the system for up to 15 minutes. They were asked to perform the motions that would be necessary during the course of the actual rehabilitative training but they were not timed or given a score based on their performance. The size of the virtual world and of the fixed objects was also tested; this would determine if a separate calibration and resizing algorithm would be necessary.

Although the subjects had varied range of motion, they all were able to reach all the necessary parts of the simulation.

Subjects were presented with a questionnaire (Appendix C) at the end of their trial. The questionnaire included 6 multiple choice questions and 2 user experience related inputs for future changes in game design. The questionnaire was designed with the help of a physiotherapist and gauges qualitatively the effect of training on the user's upper extremity function.

1. The game exercised my Elbow

1	2	3	4	5
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

Figure 5.1 Sample question from the questionnaire.

The three users' responses are shown in Figure 5.2. The average game experience for the object manipulation activities in the Tilt simulation was rated at "Neutral".

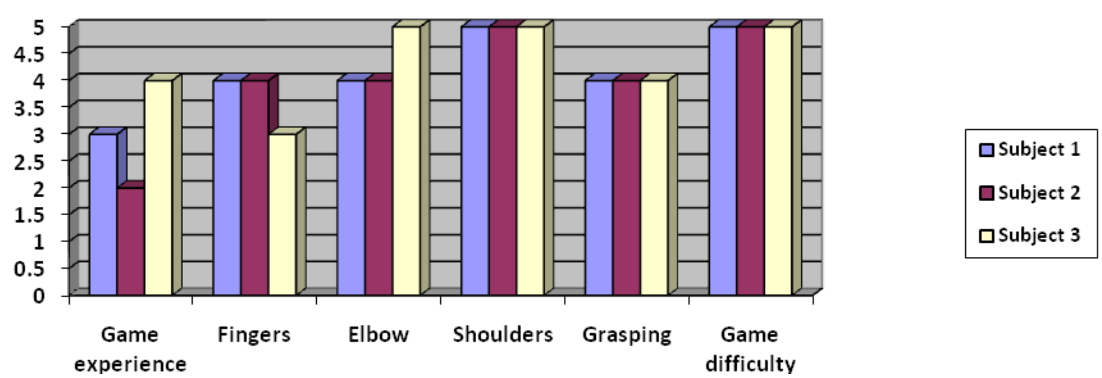

Figure 5.2 Questionnaire results.

The stroke subjects rated the overall difficulty as five on a scale of one to five. The users commented on this saying it was tiring to perform both the shoulder movements and grasping task simultaneously. Technically this determines the efficiency of the design in being able to exercise the upper extremity effectively. The difficult level of the simulation during the training can be changed to suit the level of training required by the stroke subject (refer to Section 4.3).

5.2 Qualitative Analysis

The results from the questionnaire give the qualitative proof of design for working with a stroke subject. Quantitative measurements on stroke subjects would require recruitment of subjects specifically for this study. The change due to training can be determined only if the subjects are not subject to any other training paradigms. Due to logistical difficulties, this study was not carried out as part of this thesis. Instead, a study to prove the similarity in movements in both the virtual world and real world training was compared.

One subject 25 years old was asked to use the simulation while their kinematic data was measured. Each of these healthy subjects was asked to perform a real world reach and grasp test similar to the task performed during the Tilt simulation. Figure 5.3 and Figure 5.4 show the real world and virtual world setup. The real world setup was designed based on the virtual world. The initial position of the hand was determined in the real world while the user was using the virtual world setup. A scale measured the distances moved in the X-Y plane in the real world while the user was making the required movements in the virtual world. Once the measurements were made an initial position was determined and the values were used to replicate the virtual world setup.

In Figure 5.3, the subjects are required to move their hands from initial position I, reach and grasp objects from positions B and place at target position T and return to initial position I. The objects were reset to position B after each trial by a volunteer. The subject performs the above mentioned task with objects of varying shapes and dimensions. This was followed with the subjects performing similar movement tasks with virtual objects in the Tilt simulation. The initial setup in the virtual world, used to make the measurements for the real world setup was used during the test in the virtual world. The distances between objects in the virtual world including the variation in height was measured and replicated in the real world setting. The trial lasted less than ten minutes with 5 trials each for 3 objects.

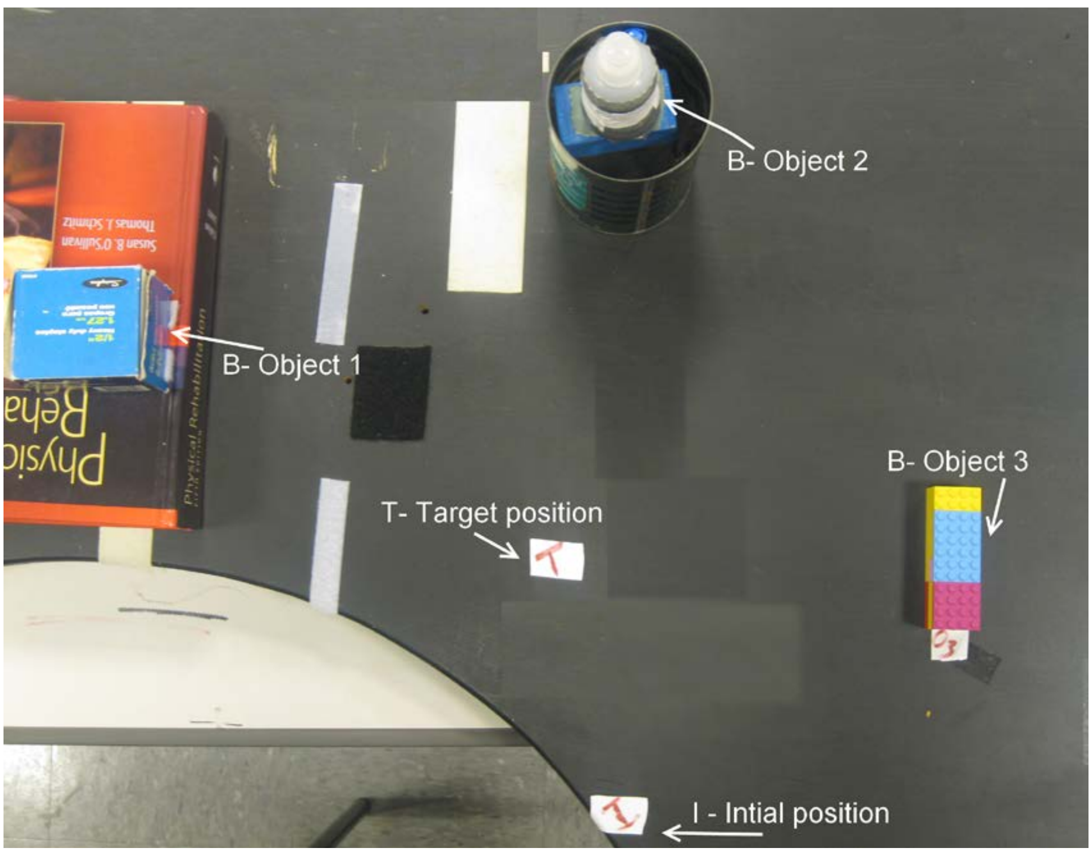

Figure 5.3 Real world reach and grasp setup.

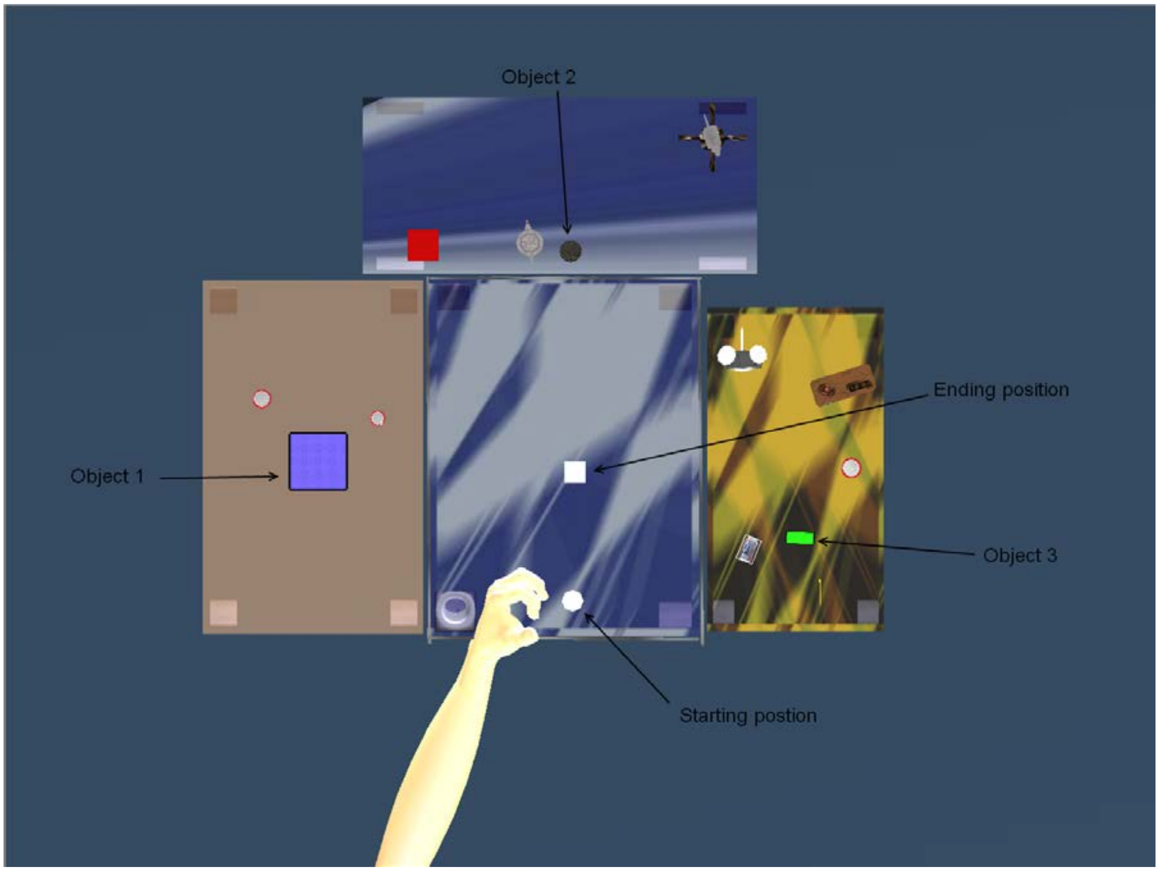

Figure 5.4 Virtual world reach and grasp setup.

Data is collected using the CyberGlove systems. The Flock of Birds system was used to simulate the movement of the arms position in the virtual world. The Flock of Birds measured the overall movement of the arm from a starting position to the target position while the CyberGlove system measured the finger movements during the reaching and grasping task.

The 3D trajectory of the arm movement generated using the x, y and z position of the Flock of Birds was visually compared. The similarities in movement between the real and virtual world was observed.

5.3 Conclusions and Future Directions

The preliminary results from the tests and validation show that the Tilt simulation was an efficient design for upper extremity training. The qualitative results show proof that the design is capable of training both the fingers as well as rest of the upper extremity in unison. The level of difficulty as faced by the stroke users was due to their inability to able to feel the object being grasped; the problem stated was lack of visual, haptic or auditory cues. Since the current system uses CyberGlove, there is no hardware based haptic feedback possible. But modifications have been made to the current system providing the users with a visual cue when an object is picked or released.

The qualitative results show the similarity in the 3D trajectory of the upper arm both in the real world as well as the virtual world. This suggests that practicing activities when using the system may be similar to real world activities of the upper extremity. Further study comparing activities using this system to comparable real world activities is required.

Training in this interactive virtual environment may provide some distinct advantages over traditional training activities with real world objects. In particular, the system allows for easy scaling of the working space. This flexibility will allow for customization of the activities to the level of abilities of the user with a disability. Moreover, the system can easily adjust the accuracy requirements for interacting with the virtual objects. In addition, speed of the arm movement required for successful trial completion can be modulated as needed by the therapist. Unlike a real world training setup, in which the size and shape of the objects to be manipulated are fixed, our system allows for wide variety of objects that would train various hand preshaping and grasping patterns.

In the future, this system flexibility can be incorporated into a user-friendly graphic-user interface. In addition, many of these parameters can be controlled by online algorithms that would be able to shape motor behaviors based on the current performance of the subject.

The platform for this system is capable of extensive real time data collection and the systematic application of activities will allow for the study of motor learning processes as they occur during task performance. Insight into this process may have important applications on the development of rehabilitation science.

APPENDIX A

OBJECT PICKER SCRIPT

This appendix shows the VSL script used for calculating the measurements and the movement of the fingers during the course of the grasping task.

```
void main()
{
        /*Assign 5 points as the end points of each of the fingers. Use physics properties and determine the collision of each of the end points. When the collision of each of the 5 points is same then count that as grasping the same object.
    If the condition is true then make the physical entity as pickable. checking the collision group of each of the end points on the left finger if the end points are touching the same object(it means they belong to the same collision group) then set the object as pickable.
    //once the object  is set as pickable, set its position equal to the position of the index finger. */

bool trigger =0;
String target;

                // cube 1
//        if (index == "cube1") (index== "cube1");

if (index== "cube1")
{
         if (middle== "cube1")
  if (ring== "cube1")
  if (little== "cube1")
        { trigger = 1;
          target= "cube1";
        }}

    //cube 5
else if (index== "cube5")
{ if (middle== "cube5")
  if (ring== "cube5")
  if (little== "cube5")
        { trigger = 1;
          target= "cube5";
        }
}

//cube 3
if (index== "cube3")
{
```

```
if (middle=="cube3")
if (ring=="cube3")
if(little== "cube3")

        { trigger = 1;
          target= "cube3";
        }
        else
        {trigger = 0;
        target = "NULL";}
}
//      else (index== middle==ring==little != "cube3")

//      getposition
```

APPENDIX B

PICKING AND GRASPING ALGORITHM

This appendix shows a snapshot of the schematic editor in Virtools. The schematic shows the 'Picking and grasping algorithm' and the 'Object Picker ' block.

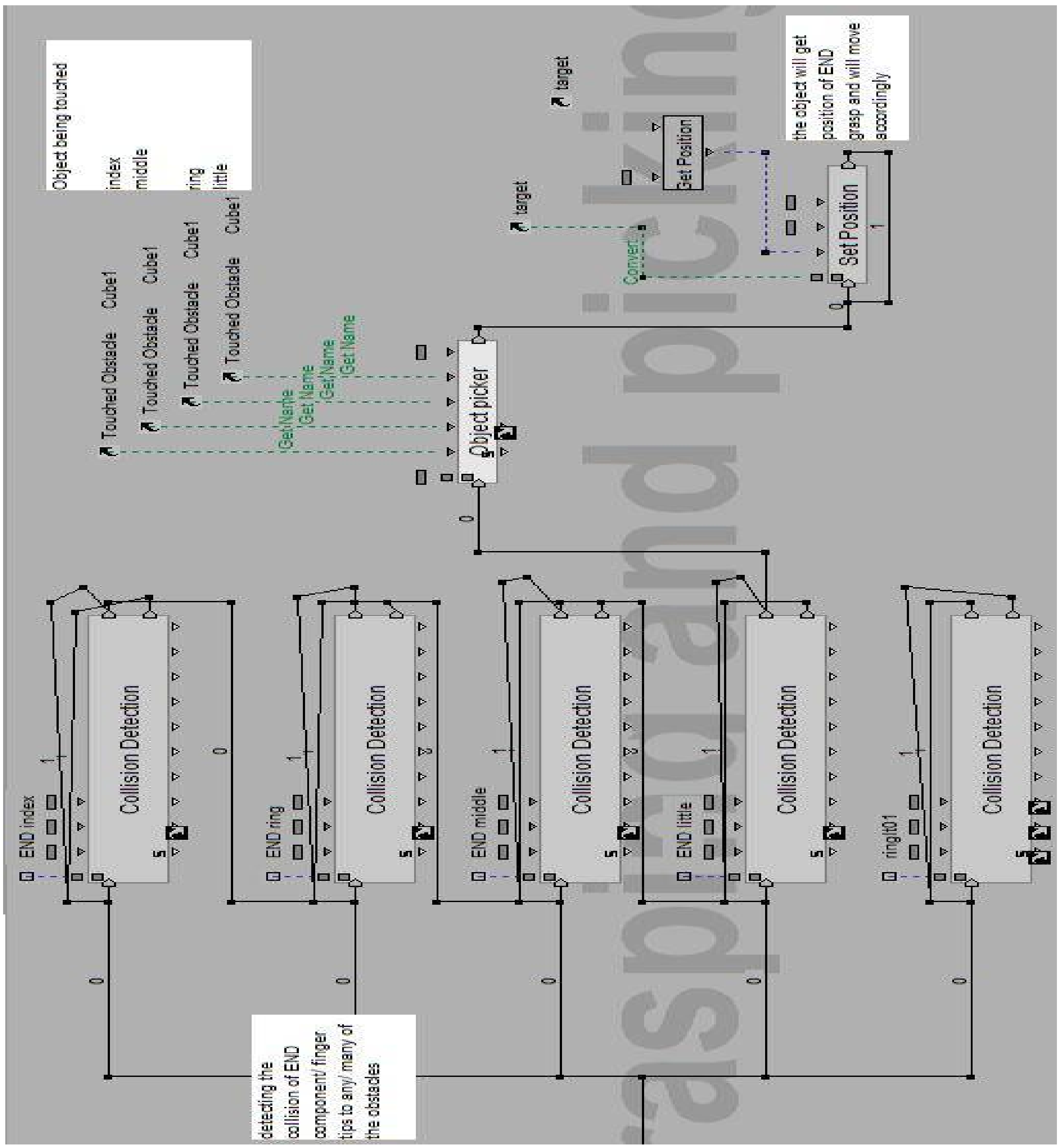

Figure B.1 Schematic representing the grasping and the reaching algorithms.

APPENDIX C

GAME EXPERIENCE QUESTIONNAIRE

Appendix C shows the questions presented to the impaired subjects after their use of the Tilt simulation. The questions mentioned below help in understanding the effect of the virtual simulation on the stroke patients.

Name: Subject   Date: xx/xx/10

1. My game experience was positive.
   1 Strongly Disagree   2 Disagree   3 Neutral   4 Agree   5 Strongly Agree
   Comments:

2. The game exercised my fingers
   1 Strongly Disagree   2 Disagree   3 Neutral   4 Agree   5 Strongly Agree
   Comments:

3. The game exercised my elbow
   1 Strongly Disagree   2 Disagree   3 Neutral   4 Agree   5 Strongly Agree
   Comments:

4. The game exercised my shoulder
   1 Strongly Disagree   2 Disagree   3 Neutral   4 Agree   5 Strongly Agree
   Comments:

5. I could tell how big or small the objects were when I tried to grasp them.
   1 Strongly Disagree   2 Disagree   3 Neutral   4 Agree   5 Strongly Agree
   Comments:

6. Was the game: Easy   OK   Difficult :
   If easy: What changes would you suggest?

7. If difficult, which task did you find difficult? / Why do you find the game difficult?

8. What changes would you like to see to make the game more interactive/ interesting?

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