VIRTUAL REALITY BASED UPPER EXTREMITY STROKE REHABILITATION SYSTEM

PRASHANT PRASHUN

A thesis submitted in partial fulfilment of the requirement of Bournemouth University for the degree of Doctor of Philosophy

March 2012

Bournemouth University

ABSTRACT

Some studies suggest that the use of Virtual Reality technologies as an assistive technology in combination with conventional therapies can achieve improved results in post stroke rehabilitation. Despite the wealth of ongoing research applied to trying to build a virtual reality based system for upper extremity rehabilitation, there still exists a strong need for a training platform that would provide whole arm rehabilitation. In order to be practical such a system should ideally be low cost (affordable or inexpensive for a common individual or household) and involve minimal therapist involvement.

This research outlines some of the applications of virtual reality that have undergone clinical trials with patients suffering from upper extremity functional motor deficits. Furthermore, this thesis presents the design, development, implementation and feasibility testing of a Virtual Reality-based Upper Extremity Stroke Rehabilitation System. Motion sensing technology has been used to capture the real time movement data of the upper extremity and a virtual reality glove has been used to track the flexion/extension of the fingers. A virtual room has been designed with an avatar of the human arm to allow a variety of training tasks to be accomplished. An interface has been established to incorporate the real time data from the hardware to a virtual scene running on a PC. Three different training scenes depicting a real world scenario have been designed. These have been used to analyze the motion patterns of the users while executing the tasks in the virtual environment simulation. A usability study with the healthy volunteers performing the training tasks have been undertaken to study the ease of use, ease of learning and improved motivation in the virtual environment. Moreover this system costing approximately 2725 pounds would provide home based rehabilitation of the whole arm augmenting conventional therapy on a positive level. Statistical analysis of the data and the evaluation studies with the self report methodologies suggests the feasibility of the system for post stroke rehabilitation in home environment.

Prashant Prashun

Virtual Reality Based Upper Extremity Stroke Rehabilitation System

LIST OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENT

In the course of pursuing this PhD degree I have incurred a debt to many people for their instruction and inspiration. There are so many people that deserve a ‘thank you’ here, so don’t feel offended if your name is not mentioned. More importantly, this list is not ordered by importance.

First of all I would like to thank Dr. Glyn Hadley for agreeing to supervise me through my PhD degree. It would not have been possible to complete this journey without his guidance, patience and perseverance during the course of my research. I really appreciated the numerous conversations we had which helped me grow as a person and improved my professional skills and at the same time was quite humbling. I would also like to thank my second supervisor Professor Ian Swain for those meetings at Salisbury hospital, arranging therapist for their feedback on the system, arranging equipments and doing several testing and making others participate in the development process. I would also like to thank my third supervisor Dr. Christos Gatzidis for his expert guidance and encouragement as well as his positive outlook to the overall research.

I would also like to thank Dr. Duncan Wood from Salisbury District Hospital for letting use the Xsens sensors. Apart from my supervisory team I would also like to thank Professor Mark Hadfield for giving me proper guidance and support. I would like to thank my Research Administrator Naomi Bailey, colleague and friends for spending quality time with me and helping me emotionally whenever I felt lonely in and out of the department and my thanks to my landlord Steve Collins for all the help during my stay at his place.

Sincere thanks to my Brothers and Sister-in-laws for their love and invariable support throughout this journey. This work is dedicated to my dear Father and Mother, without their love and upbringing I could not have been the person I am.

AUTHOR'S DECLARATION

This work contained in this thesis is the result of my own investigations and has been accepted or concurrently submitted in candidature for any other award.

LIST OF ABBREVIATIONS

ADLs: Activities of Daily Living

DIP: Distal interphalangeal joint

DOF: Degrees of Freedom

GUI: Graphical User Interface

MP: Metacarpophalangeal joint

OT: Occupational Therapy

PIP: Proximal interphalangeal joint

PT: Physical Therapy

ROM: Range of Motion

3D: Three-Dimensional

BBT: Box and Blocks Test

CAVE: Computer Augmented Virtual Environment

CIMT: Constraint Induced Movement Therapy

HMD: Head Mounted Display

SD: Standard Deviation

UE: Upper Extremity

UL: Upper Limb

VR: Virtual Reality

CHAPTER 1. Introduction

Technological advancements in physical medicine and rehabilitation have opened several possibilities for exploring the opportunities for its suitable uses in the healthcare systems. Different fields have approached technology to better the outcomes in diagnostics and rehabilitation in a number of pathologies. However there are still certain areas which seek improved results in terms of technological interventions especially the rehabilitation of conditions related to brain dysfunction. This thesis aims at making a contribution to such systems which investigates the use of new technologies for the rehabilitation of motor dysfunctions following brain dysfunctions in particular due to stroke. Stroke is the third biggest cause of death and the leading cause of disability in the United Kingdom. About 110,000 people in England and around 140,000 in UK suffer from stroke each year and about 75% of the people require multi-disciplinary assessments and rehabilitative treatments (Intercollegiate Stroke Working Party, 2008). From the majority of people suffering from stroke, a lot of them are left with life-long cognitive and/or motor disability of the upper extremity (affecting functionality of shoulder, arm and hand). Over 50% of patients with upper limb paresis resulting from stroke face long-term impaired arm function and ensuing disability in daily life (Verbunt, *et al.* 2008). The recovery process after stroke puts a lot of burden on the infrastructures and rehabilitation expenses. Due to the increasing cases of stroke and the limited number of rehabilitations hospitals, equipments and therapists, patients are barred from desired long term post stroke rehabilitation. There lays a huge burden on the health care system in providing rehabilitation to the patients discharged from the hospital. The number of therapists required for assessing and rehabilitating the stroke patients are not sufficient, and sometimes they are unable to meet the demands of long and repetitive sessions needed by the patient for fast recovery. There is also an insufficiency of instrumented assessment equipment appropriate for use at home that can augment and evaluate current rehabilitative interventions. Therefore there arises a considerable interest in training aids or intelligent systems as complementary tools to support rehabilitation. This encourages research work worldwide to design intelligent and efficient strategies which strengthens and compliments the rehabilitation process and supports faster recovery. It is difficult to tackle the recovery process solely by investigating the neuronal reorganisation as it is unclear how the reorganisation can be effectively mobilized. Novel technologies based neurorehabilitaion holds promise to in addressing this issue. Virtual reality which was considered as a tool used only for entertainment purposes now seems to be a promising tool capable of stimulating and enhancing motor recovery. One of the advantages of virtual reality technology is that it can be shaped to address the specific requirements for an effective rehabilitation treatment. It has been shown that a varied and rich rehabilitative environment can benefit the recovery process in physical rehabilitation of the stroke survivor (Carr & Shepherd 2003, Keshner 2004).

This thesis describes the design, development and the assessment of a virtual reality based system specifically designed to promote game like interaction of the upper extremity in enhancing motor recovery following neurological damage. The virtual reality based stroke rehabilitation system was designed, developed and applied taking in to account the mechanism of the brain recovery. The virtual reality based stroke rehabilitation system tracks the upper extremity and finger movements in order to map them on to a virtual environment. Two Inertial sensors from Xsens Technologies and a Data glove from DGTech have been used to track the upper extremity movement and the finger flexion/extension.

1.1 Motivation

The motivation for carrying out this research stemmed from our review of the state of art of the technologies used in the rehabilitation of stroke patients. The key issues of using most of the technologies are their limitations in terms of cost, complexity and in providing suitable environments for patients to undertake their treatments. In the first instance, virtual reality (VR) seemed to provide a means of overcoming these problems. An initial review (CHAPTER 3 Technological Interventions) of the field revealed that many such research projects have been undertaken in the past years, each approaching the technology from differing points of view. There is still a need (CHAPTER 3 Technological Interventions) for the whole arm/hand VR based system which could be simple, relatively low cost (affordable or inexpensive for a common individual or household) and easy to use as a home-based assessment and rehabilitation tool.

1.2 Research Approach

This thesis focuses on the importance of a virtual reality application in a home based rehabilitation setting. Specifically this would entail the development of a rehabilitation prototype that would provide whole arm rehabilitation. The integration of a motion tracking technology and a finger flexion sensing glove is achieved to administer whole arm rehabilitation. A trial of the system was conducted on 10 healthy volunteers and 10 stroke simulated volunteers with the movement constraint splint on. Each subject was asked to wear the motion sensors and VR glove and perform series of tasks in a virtual environment displayed on a computer screen with measured repetitions. The orientation and position of the upper extremity and the fingers were measured during the trial of the motor skills. Movement times and accuracy were analyzed in order to check the reliability of the system. Questionnaires were used to obtain feedback from the volunteers at the end of the trial in order to evaluate the system.

1.3 Terminology

This section would include the frequently used terms throughout the main body of the thesis. Some of the terms which have been used may have multiple definitions. The preferred definition will be identified in all such cases and used exclusively in the remainder of the thesis.

Virtual Rehabilitation: The rehabilitation process which is entirely based on the virtual reality simulations or provided within the framework of the conventional therapy is called virtual rehabilitation (Burdea 2002).

Virtual Reality (VR): It is defined as an artificial environment created by the use of software's and computer peripherals which gives a user the feeling of a real world place or event. Virtual reality occludes some part of the real world environment from the user with computer generated elements. VR is unlike augmented reality which seeks to enhance or alter the real world. Virtual reality environments are primarily visual experiences frequently perceived using shutter glasses & desktop monitors (fish tank VR), VR caves, or head-mounted displays, but sound and touch can also be part of the virtual experience (Brooks 1999).

Virtual Environment (VE): The environment simulated by a virtual reality system. An immersive virtual environment is a sub-class of VEs where visual perception of the real world is obscured almost completely by the virtual world (Kalawsky 1993).

Immersive: Immersion is a state of being so focused on a specific experience that there are no distractions (Garu 2003).

Haptic(s): The word haptic device from Greek haptesthai meaning in touch. Haptics deals with the interaction of a three dimensional environment created in a computer, which besides the visual impression gives the user a physical interaction with an object with a force feedback device (Monkman 1992).

Hemiparesis: It's the weakness observed by one side of the body after stroke. Hemiparesis leads to the reduced muscular strength of the affected part of the body which tenders constrained movement (Bobath 1990).

Viewing Screen: The viewing screen in our case is the PC monitor where the virtual simulations are running (Angel & Shreiner 2011).

View Frustum: The bounding area of the virtual environment that is visible to a virtual camera. A virtual camera has a 4 sided viewing pyramid expanding out (to infinity) from the center of projection in the camera's gaze direction. The view frustum is defined by two parallel planes intersecting the viewing pyramid. The six sides of the frustum each define a clipping plane determining what objects are displayed in the scene (Angel & Shreiner 2011).

Calibration: To precisely adjust data or objects for a particular function. The virtual environment is calibrated with the real time input from the motions sensors and the virtual reality glove using the method described in Chapter 6. Sensor calibration refers to the process of standardizing sensor information so that systematic errors or deviations in data can be determined and a proper correction factor applied (Douglas *et al.* 2007).

System Lag: The time between when a user's action occurs and the time a result is presented to the user (Nise 2004).

Refresh Rate: The frequency that the virtual scene is changed or updated. We will also refer to update rate as the frame rate. We calculated the update rate by taking the average time interval between virtual scene drawings/renderings calls over a one second interval (equivalent to the number of render calls per second). The average update rate during the experiment was 60Hz which is the default OpenGL refresh rate on windows XP (Shreiner and Angel 2011).

1.4 Thesis Outline

Chapter two is a review of the conditions leading to the upper extremity movement disability. It will provide an insight into stroke, related disability, especially upper extremity motor disabilities and the preventive measures.

Chapter three describes the technological interventions in upper extremity stroke rehabilitation with a virtual reality perspective. Also, it details the research carried out in the filed of virtual reality to enhance the capabilities of virtual reality in upper extremity stroke rehabilitation.

Chapter four entails the design and physical implementation of a 2D system, for the testing of accuracy, repeatability and error in the measurement of the end position using motion sensing technology. This design serves as a baseline, reference for the later stage of results validation in Chapter 6, during the system trial on healthy volunteers.

Chapter five presents the design and development of the virtual environments for the interactive rehabilitation. Collision detection of the virtual upper extremity with the virtual objects has been presented highlighting some collision detection and human modelling techniques.

Chapter six presents the system trial of the developed virtual reality based stroke rehabilitation system on 10 healthy volunteers and 10 stroke simulated volunteers. Statistical analysis of the data has been provided to enumerate the outcomes. Evaluation Questionnaires has been analyzed in order to document written feedback from the users of the system.

Chapter seven presents the conclusion, discussion, thesis contribution and future research directions.

CHAPTER 2. Stroke and Its Consequences

Stroke is defined as the condition of the brain caused due an abnormality in the blood supply (Caplan 2006, MacWalter and Hazel 2003). Ischemia and haemorrhage are the two broad types of stroke. Ischemia is caused due to the lack of blood supply in brain where as haemorrhage occurs due to the escape of blood from a ruptured blood vessel Figure 2-1. Ischemia is much more common than haemorrhage and four out of five people detected with stroke symptoms are ischemic (Caplan 2006, Squire, Albright *et al.* 2009). Hence around 80% strokes are ischemic stroke. There are different types of brain ischemia but the most common among them are thrombosis (formation of blood clot inside a blood vessel), embolism (occurs when a blood clot or an air bubble, travels through the bloodstream before becoming lodged in a blood vessel blocking the flow of blood), and systematic hyperfusion (reduction of blood flow to all parts of the body) (Squire, Albright *et al.* 2009).

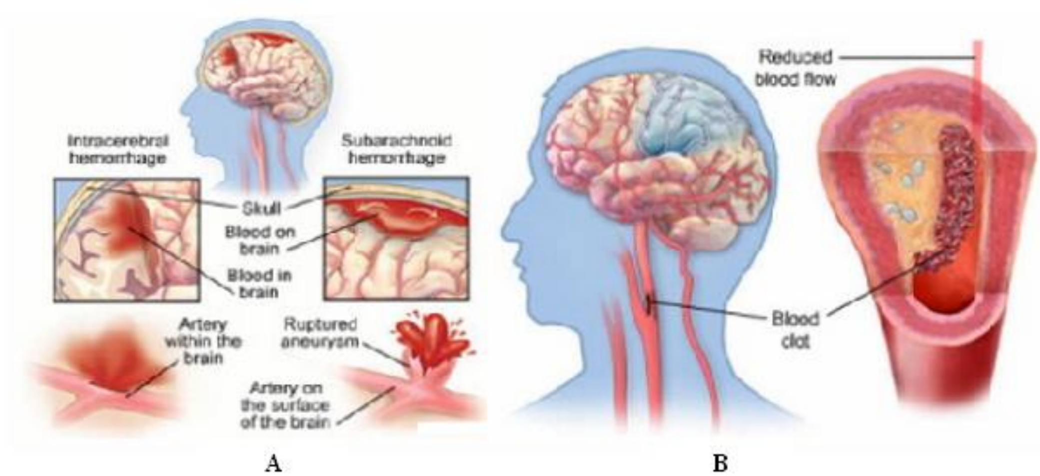

Figure 2.1 (A) Hemorrhagic (B) Ischemic Stroke (Stroke Association, 2012)

Atherosclerosis is the most common disease that narrows the blood flow channel (lumen) in an artery. Due to the narrowing of the lumen, blood flow is severely reduced; causing localized stagnation of the blood column. This change in blood supply causes the blood to clot, resulting in total obstruction of the artery.

Apart from the stroke caused due to the obstruction in the blood supply to the brain, there are other factors that lead to stroke. The most common of these factors are hypertension, heart disease, smoking, drug abuse obesity and genetic factors. Poor diet, lack of physical activity, over drinking, stress and depression along with the above mentioned causes account for around 90% of strokes (O'Donnell *et. al.* 2010). According to O'Donnell, poor diet increases the risk by 35%, stress increases the risk of stroke by 30% and depression tends to increase the risk by 30%.

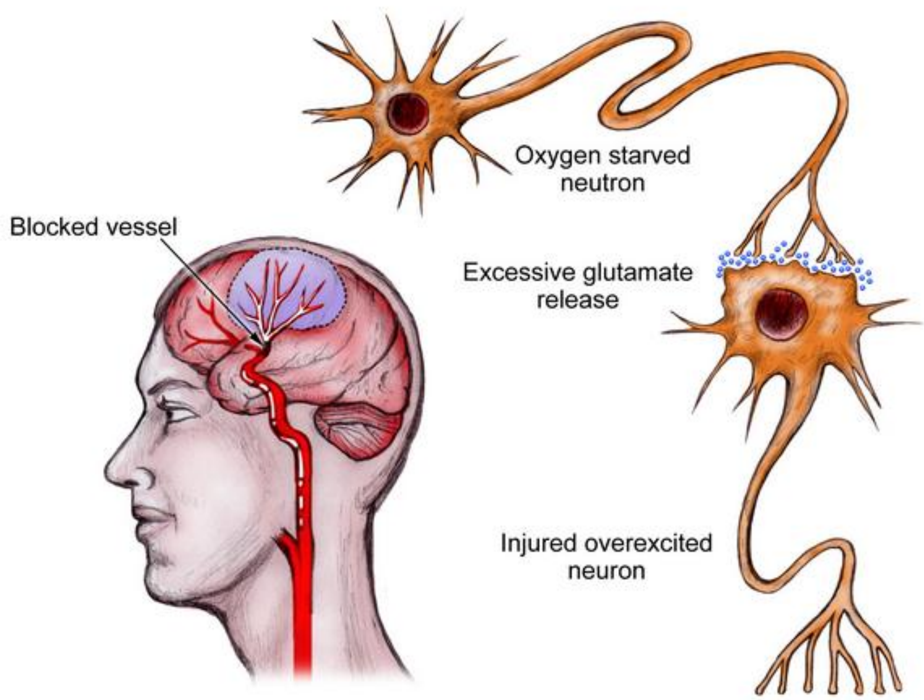

Figure 2.2 Cellular mechanism behind stroke (Bruno-Petrina, 2012)

When a stroke occurs it leads to the initiation several damaging collateral events in the brain. The neuron releases glutamate onto nearby neurons, exciting them and leading them to release calcium and eventually death. During an injury there is a change in Normal neurotransmission which causes excess calcium production.

This promotes the activation of enzymes, eventually leading to destruction of the cell. The glutamate receptors such as N-Methyl-D-aspartate (NMDA) receptors are responsible for this occurrence and it has been sought that the damage can be stopped through the use of agents that block these receptors (Garcia *et al*. 1994). The cellular mechanism in stroke is given in Figure 2.2.

There can be a number of symptoms caused by different kinds of strokes. These depend on the type of stroke and the part of brain affected.

Depending on the type of stroke and the part of the brain affected, symptoms of stroke can be divided into a number of categories. The symptoms of stroke usually last for seconds or minutes. Sometimes symptoms may subside but that would mean that the person might be under the influence of transient ischemic stroke (TIA), i.e. mini stroke. Also, signs and symptoms of stroke may vary from person to person.

2.1 Stroke Symptoms

The onset of stroke is detected and classified from the symptoms shown which occur when a part of the brain stops functioning properly or due to the vascular cause (Caplan 2006). Subjects may experience weakness that would lead to loss of strength and coordination in one or more limbs. The symptom of weakness occurs due to loss of brain function and is very common in case of stroke. The weakness can very well be confined to a specific body part such as hand, but usually it is experienced in more than one area on the same side of the body.

A number of other symptoms are also seen in the patients with the probability of a stroke. These include, numbness in the body parts; loss of vision; dizziness, vertigo and loss of balance and coordination, abnormality of memory, thinking and behaviour; speech and language difficulty (Caplan 2006) Figure 2.3. These common symptoms after stroke have a considerable effect on the activities of daily living which involve personal care, transferring recreational activities and leading a healthy home life. These basic restraints prohibit a stroke subject from wholly participating in work and limit their sphere of social interactions (Tennant *et al.* 1997).

The conditions of an individual suffering from stroke as outlined in the following framework by the World Health Organization's (WHO) international classification of impairments, disabilities and handicaps (ICIDH) (Post *et al.* 1999, Wade *et al.* 1985) are:

- Pathology (disease or diagnosis): operating at the level of the organ or organ system
- Impairment (symptoms and signs): operating at the level of the whole body
- Activity limitations (disability): observed behaviour or function
- Participation restriction (handicap): social position and roles of the individual

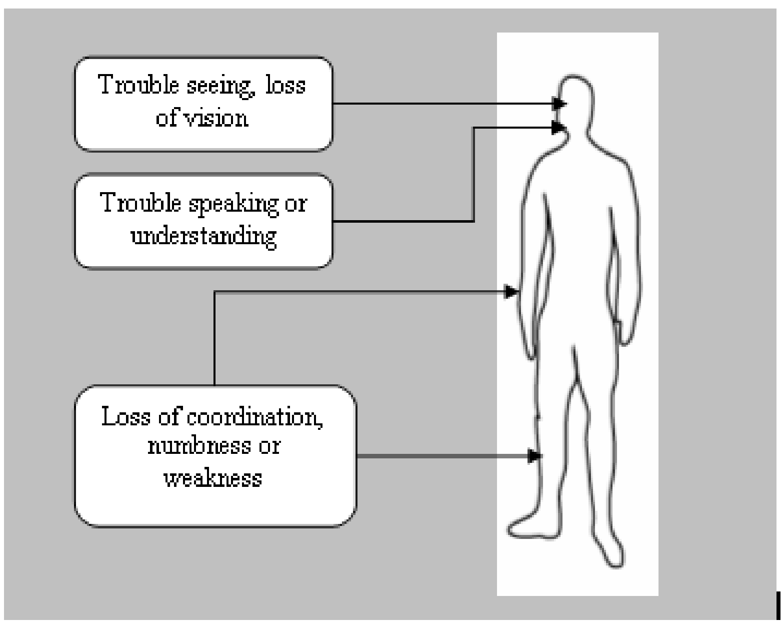

Figure 2.3 Common Symptoms of Stroke

Normal motor control is an essential pre-requisite to execute the activities of daily living. The loss of motor control could account for muscle weakness, hyperactive reflexes, and abnormal muscle synergies.

Property	Name of Scale
Consciousness Level	Glasgow Coma Scale
Stroke Deficit	NIH Stroke Scale Canadian Neurological Scale
Global Disability	Rankin Scale
Disability in ADL	Barthel Index Functional Independence Measure
Mental Status	Folstein Mini-Mental State Examination Neurobehavioral Cognition Status Exam (NCSE)
Motor function	Fugl-Meyer Assessment Test Motor Assessment Scale Motricity Index
Balance	Berg Balance Assessment
Mobility	Rivermead Mobility Index
Spasticity	Ashworth Scale
Speech and language	Boston Diagnostic Aphasia Examination Porch Index of Communicative Ability (PICA) Western aphasia Battery
Depression	Beck Depression Inventory (BDI) Center for Epidemiologic Studies Depression (CES-D) Geriatric Depression Scale (GDS) Hamilton Depression Scale
Instrumental ADL	PGC Instrumental Activities of Daily Living Frenchay Activities Index
Manual Dexterity	Box and Block Test Nine Hole Peg Test
Family	Family Assessment Device (FAD)
Health status/ quality of life	Medical Outcomes Study (MOS) Sickness Impact Profile (SIP)

Table 2-1: Methods of assessing the impact of Stroke

One of the commonest impairments after stroke is hemiparesis. From the total population of stroke victims around 88% of patients with acute stroke have hemiparesis.

In order to assess the severity of stroke and the motor dysfunction resulting from the trauma, diagnostics are conducted through imaging techniques. Some of the common imaging techniques in use are Computed Tomography Scans and Magnetic Resonance Imaging and neurological examination. The most widely used tests to measure the severity of stroke are given in Table 2.1. Based on the initial symptoms, stroke can be classified into different categories. The doctors study the symptoms of stroke to determine the brain dysfunction and hence the type of impairment. The corresponding components of dysfunction are described as impairment, activity limitation, and participation restriction.

2.3 Stroke Impacts on Upper Extremity Functions

The upper limb function basically comprises of two groups of actions: reaching/pointing (arm function) and grasping/releasing/manipulating (hand function). Studies have shown that about 65 to 85% (Wade 1983, Studenski *et al*. 2006) of the people suffering from stroke report the loss of arm functions and around 55 to 75 % report continued functional limitations up to 3-6 months after stroke (Feys *et al.* 1998; Broeks *et al*. 1999). It has been reported that only about 11 to 18% of the people with stroke are able to gain full upper extremity function (Nakayama *et al*. 1994; Kwakkel *et al*. 2003, Hendricks, van Limbeek *et al*.2002). The enduring upper extremity disabilities after stroke provide the subjects with no other choice than to remain in the home environment with continued difficulties in activities of daily living ADLs (Thorngren *et al*. 1990; Taub *et al*. 1994; Mayo *et al*. 2002).

The contralateral primary motor cortex controls the motor functions of the upper extremity in the right handed subjects (Foulkes *et al.* 1988). There are other motor pathways which are closely associated with the normal functioning of the motor activities in the subjects such as premotor cortex, supplementary motor areas, parietal cortex, and subcortical or brain stem. Any mishap or abnormality brought about in these areas controlling the motor functions can cause contralateral hemiparesis or hemiplegia, a common neurological ailment in stroke.

Stroke severely damages the primary motor pathway called the corticospinal pathways. Motor pathways originate in the brain or brainstem and descend down the spinal cord to control the alpha-motor neurons.

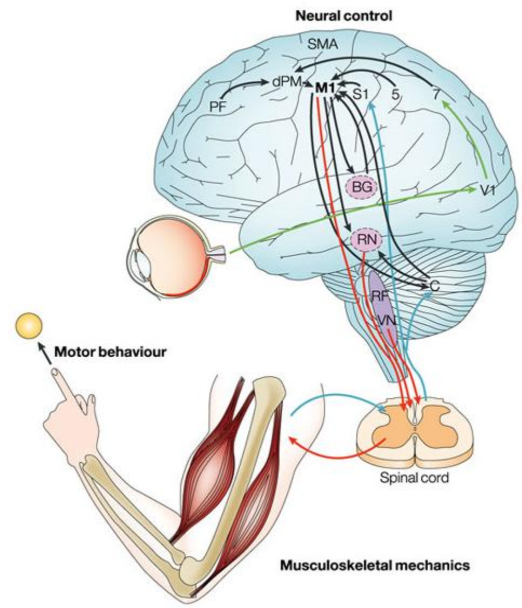

Figure 2.4 Neural Pathways involved in Motor Coordination (Scott 2004)

These neurons are responsible for controlling the muscles. The motor pathways also control posture, reflexes, and muscle tone as well as the conscious voluntary movements. Acute upper motorneuron (UMN) lesion leads to some major impairment of upper limbs such as changes in muscle performance which interferes with some functional motor performance (Landau 1980). These impairments are paralysis and weakness (decreased muscle force), and loss of dexterity (disordered coordination). Spasticity (velocity dependent stretch reflex hyperactivity or hyperflexia) does not always contribute to motor disability following stroke (Lance 1980). Impairments such as depressed motor output, decreased rate of neural activation, poor timing and coordination of segmental movements and sensory deficit also severely impact upper limb functional performance (Carr and Shepherd 2006). Figure 2-4 shows motor cortex and neural pathways important for upper extremity voluntary motor control (Scott 2004).

It can be seen from the diagram that the blue arrows are the neurons which are protruding from sensory/proprioceptors and provide crucial information when reaching the brain. The red arrows carry the information or the commands from the brain to manipulate the muscles to cause contractions. Spinal cord plays the vital pathways for discharging and receiving the exchange of information. From the figure it can be noted that all the neurons travel to the primary motor cortex (M1). Also motor neuron intervene the basal ganglia (BG) and the cerebellum (C). Motor cortex, basal ganglia and the cerebellum are the three regions which are critical in coordinating the movement (Scott 2004).

Some of the prominent motor dysfunctions of the upper extremity as a result of a lesion followed by stroke are muscle weakness, spasticity, abnormal muscle synergies, hyperactive reflexes, muscle atrophy, and increased joint stiffness.

The damage caused in the motor-cortex neurons or corticospinal projections results in the ill activation of the spinal motor neurons which control the muscles. According to Harris and Eng (2007), muscle weakness tends to limit the maximum potential output force of a muscle. Muscle fatigue emerges from this damage and hence the strength diminishes as a result. Since the muscle weakness tends to limit the use of the upper extremity its prolonged lack of use may lead to further decreased strength of the muscles. The asymmetry of signals from the brain and central nervous system to the muscles causes spasticity. It could also be described as a motor disorder characterized by a velocity dependent increase in tonic stretch reflexes (muscle tone) (Lance 1980). Increased muscle tone, or overactive reflexes, delayed motor development or functional abilities, bone and joint deformities are some of the indicators of spasticity. Spasticity could be diagnosed by some of the few tests such as passive and active range of motion and individual's abilities to perform the activities of daily living.

Damage to the upper motor neuron also causes hyperactive reflexes which tend to resist or even temporarily reverse desired movements. Hyperactive reflexes increase muscle tone or joint resistance. Hyperactive reflexes are thought to be caused by increased neural background activity of the motor neurons in the spinal cord, increasing both the motor neuron excitation and excitability.

Neurological deficit also causes abnormal muscle synergies which are sign of vertebrate movements. Abnormal muscle synergies lead to loss of independent joint control which affects the outcome of voluntary movements. As observed by (Beer *et al.* 2004, Sukal *et al.* 2007, Ellis *et al.* 2008) when an individual tries to reach up and out for an object on a shelf, the abduction torque in the shoulder causes an involuntary flexion of the elbow, reducing the achievable reaching distance of the hand. Abnormal muscle synergies may further lead to muscle atrophy and increased joint stiffness.

Disuse of muscle could cause muscle atrophy which slowly decreases muscle mass over time (Hafer-Macko *et al*. 2008). Long term muscle weakness results from muscle atrophy which limits movements of individuals after stroke and decreases strength of the upper extremity. People with stroke also experience increased joint stiffness due to changes in muscle and tendon properties. Abnormal muscle co-activation patterns or spasticity leads to these changes.

It could be concluded that the motor impairment could either be severe, moderate, or mild. In the case of severe impairment muscle activation is almost absent or there is hardly any limb movement observed. In the case of moderate, limb movements still continue to be affected, where as in the case of mild impairments motor control of the upper extremity could be close to a functional range.

2.4 Rehabilitation Post Stroke

Cortical reorganization around the damaged brain or unmasking the latent neural networks has been reported to speed up recovery after stroke (Johansson 2000; Butefisch 2004; Krakauer 2005; Nudo 2006; Murphy and Corbett 2009). Improvement of motor skill depends on neurological recovery, reworking and learning new strategies and motor programs. The reorganizational processes in the brain have been demonstrated both early on and later after a stroke; associated with the intensive use of the affected arm (Carr and Shepherd 2006). There are mainly two types of processes underlying functional recovery from hemi paretic stroke: reorganisation of affected motor region and changes in unaffected hemisphere (Carr and Shepherd 2006). A subject adhering to exercises and training being conducted at regular intervals constantly can also bring about effective functional connections within the remaining brain tissue. Training and practice using facilitative motor learning or relearning is essential to the formation of new motor connections. Recovery is minimal in some individual, particularly those with an initially severely paretic limb. Reports of recovery of functional use irrespective of initial impairment vary from 5% to 52% (Gowland 1982, Dean and Mackey 1992, Carr and Shepherd 2006). There are disagreements in the assumptions suggesting recovery post stroke which takes place within the first three months where as clinical evaluations have shown improved performance more than a year post stroke. These clinical studies have been done on patients with some active finger and wrist movements (Duncan *et al*. 1994, Taub *et al*. 1993, Liepert *et al*. 1998).

With a diverse set of stroke subjects with varying types of stroke type and functional deficits it is immensely challenging task to constitute a rehabilitation strategy. Rehabilitation of the subjects tends to bring their dependence on their family or close relatives to minimum. To devise a tangible rehabilitation strategy for stroke survivors, there are different levels of involvement of expertise from different fields. Some of the medical professional who are involved in the rehabilitation process are physician, rehabilitation nurses, physical and occupational therapists (Post-Stroke Rehabilitation 2000). Physicians are responsible for recommending rehabilitation programs and care for patient's health and providing guidance in preventing a second stroke.

In a healthy individual, the upper extremity undergoes a full range of motion patterns when not affected by any lesion. The normal range of motion for the shoulder, elbow, and wrist joints are given in Table 2.2. The normal range of motion of the shoulder, elbow and wrist are shown in Figure 2.5.

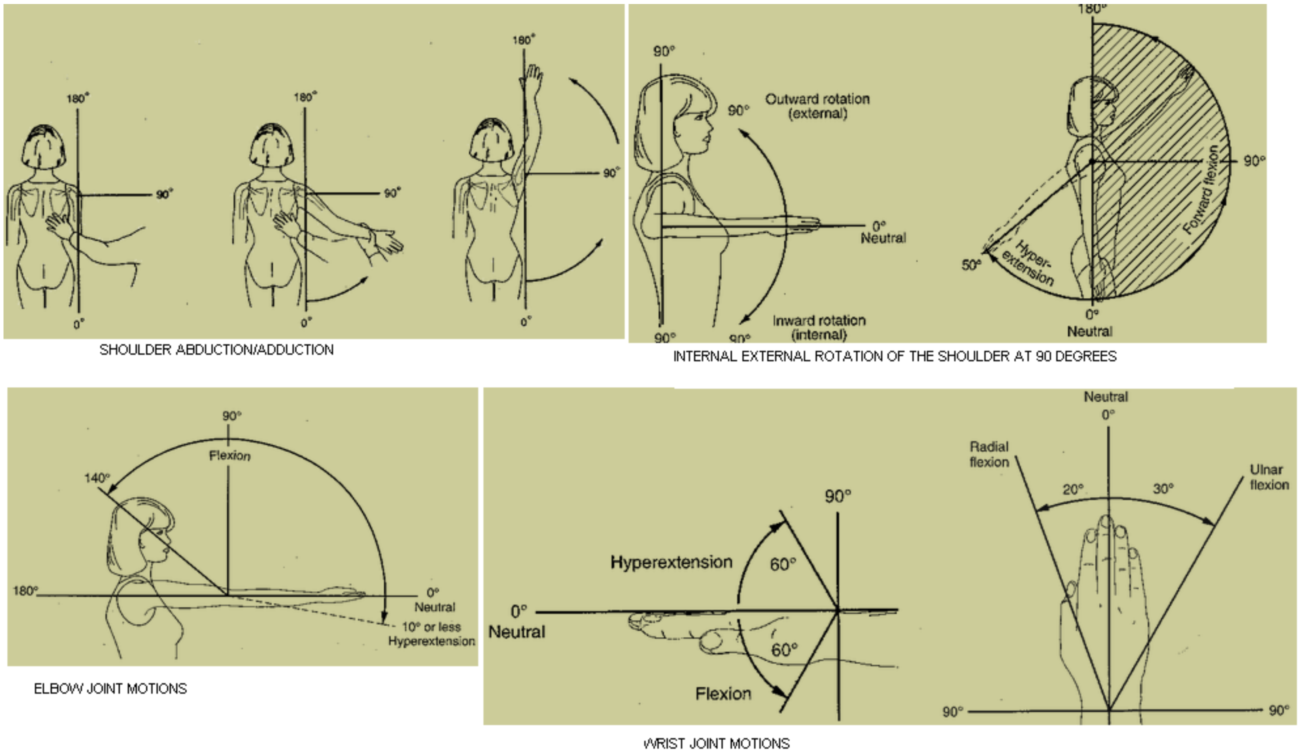

Figure 2.5 Movement System in the Upper Extremity (Adapted from Luttgens & Hamilton, 1997)

Shoulder (Degrees)	Elbow (Degrees)	Wrist (Degrees)
Flexion (0-180)	Extension/Flexion (0-145)	Extension/Flexion 70/80
Hyperextension (0-50)	Pronation/Supination (80)/90	Radial Deviation 0-20
Abduction (0-180)		Ulnar Deviation 0-45
Inward Rotation (0-90)		
Outward Rotation (0-90)		

Table 2-2 Normal Joint Range of Motion

Motor dysfunction affects the normal range of motion which needs to be considered when laying down the rehabilitation strategies.

Before the rehabilitation process starts the patients need to be assessed for motor control, range of motion, balance and their ability to tolerate the prescribed exercise. Once the assessments are complete, a therapist designs a programme to improve the condition of the patient.

Finally the patient's recovery could be tested by one of the following tests like the Fugl Meyer tests or the Functional Independence Measure (FIM). Since the upper limb is used to carry out most of the activities of daily living such as drinking, eating, clothing, bathing its rehabilitation is of prime importance. The focus of the upper limb rehabilitation revolves around restoration of the motor functions in the affected upper limb, improving the execution of the activities of daily living (ADLs) and recovery of the previously performed functions (Cerullo 1986).

MCP (Degrees)	**PIP (Degrees)**	**DIP (Degrees)**	**MCP Thumb (Degrees)**	**PIP Thumb (Degrees)**
Abduction (0-25)	Flexion (0-120)	Flexion (0-80)	Abduction (0-50)	Flexion (0-90)
Adduction (20-0)			Adduction (40-0)	
MCP Flexion (0-90)	Extension (120-0)	Extension (80-0)	Flexion (0-70)	Extension (90-0)
MCP Extension (0-30)			Extension (60-0)	

Table 2-3 Normal Range of Motion of Finger Joints

Exercises which involve activities of daily living such as self care, management of environmental devices and home activities helps patients regain their lost motor functions

(Pedretti 1985). Therapists need to tailor these tasks keeping in mind the style and ability of the patients (Pedretti, 1985).

Due to stroke an individual is subjected to abnormal motion patterns of the upper extremity wherein they try to adapt certain movements for the execution of tasks. The adaptive movements can either be due to muscle weakness, degree of inter-joint coordination. Lack of joint and muscle flexibility due to soft tissues length also changes, leading to increased muscle stiffness (Carr and Shepherd 2006). The typical examples of adaptive movements during attempt at arm use are given in Figure 2.6.

When a stroke subject tries to reach for an objects which is within the range of his or her arm length, in doing so they try to bend/flex their hips instead of flexing their shoulder due to the movement constrain produced after stroke. Once the rehabilitation process starts the shoulder flexion improves reducing the flexion at the hips. When reaching forward the stroke subjects show abnormality in shoulder girdle elevation, lateral flexion of spine, abduction of shoulder with elbow flexion, internal rotation of shoulder and pronation of forearm. During the execution of a task which involves grasping an object, when a stroke subject opens his/her hand excessive opening is observed to compensate for any potential inaccuracies. At the time of releasing an object in a sequence of pick and place activity, compensations are observed during finger extension when the wrist is flexed due to contracted long finger flexor, weak wrist extensors, extension of thumb at carpometacarpal joint (CMCJ) and metacarpophalangeal joint instead of abducting at CMCJ. While grasping an object, a stroke subject shows a compensatory movement in terms of poor control as they apply excessive flexor force during grasping.

Other compensatory movements are observed in terms of the uses of the non-paretic limb preferentially when active movement is possible, and subsequent 'learned non-use'. Habitual posturing of the paretic limb, leading to adaptive length-associated changes to soft tissues including loss of extensibility and increased stiffness of muscle. Joint stiffness and pain, particularly affecting glenohumeral (GH) joint and wrist.

Taking into account the compensatory movements an intelligent training module need to be planned to improve the action of the upper extremities. The training module must consist of tasks which later transform and correct the movement of the upper extremity while moving objects within the arms length, reaching for objects irrespective of direction. The manipulation of objects for specific purposes need to be taken into account and holding, transporting objects from one place to another are some of the tasks which need to be well planned for reducing compensation. For the hand and finger movements and improvement of compensations pick and place of objects of different shapes, sizes, weights and textures are considered.

The exercise and training need to be specific to task and context, i.e., related specifically to the tasks to be learned. It is challenging to develop effective methodologies looking at the complexity of upper limb functioning and nature of lesion.

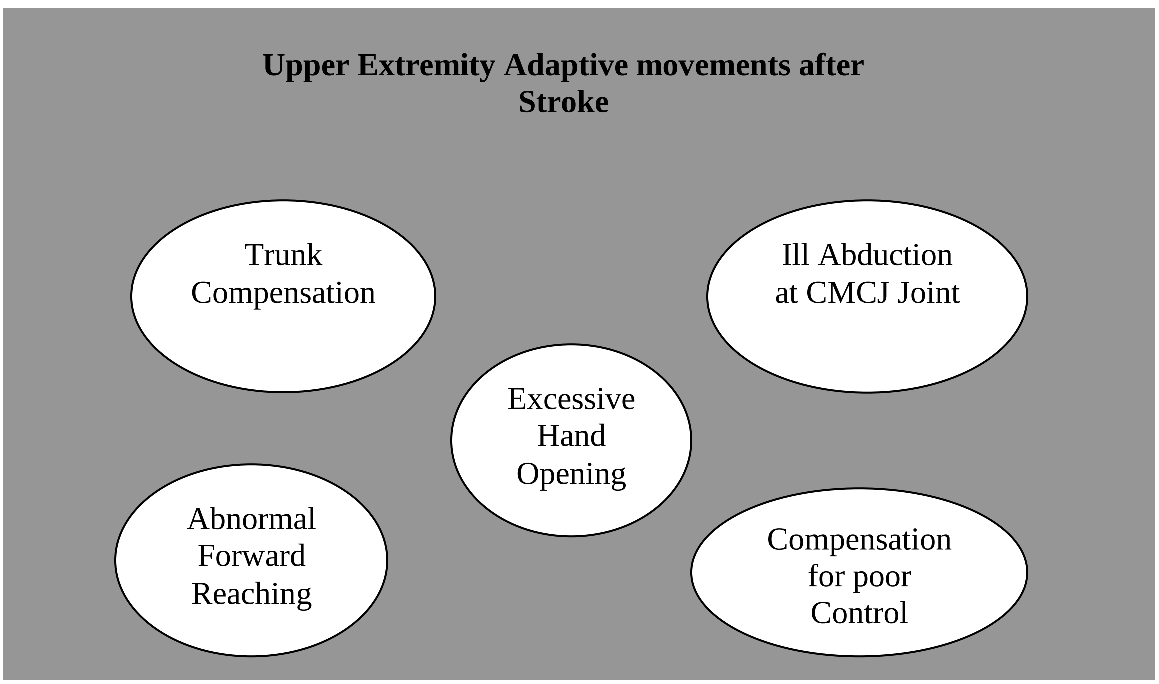

Figure 2.6 Adaptive movements during attempts at arm use

Some of the interventions which are required and have been found to be effective for stroke patients with some unforced motor function early after stroke are (Carr and Shepherd 2006):

- Repetitive exercise for wrist (wrist extension, finger flexion and extensions).
- Forced use (with constraint of non-paretic arm) and intensive exercise and task training.
- Bimanual training (hand/arm bimanual therapy).

There are a great majority of stroke patients who improve, some even return to normal or near normal functioning (Caplan 2006). Many go back to previous work, resume the same activities and interests they had before. Most of them require one or the other kind of rehabilitation technique for regaining their normal functioning. Both physical and occupational therapist identify components which can provide focus for training and further guide the analysis. They identify what is critical to emphasize in the training.

Rehabilitation is also referred to as the professional help in promoting recovery. Rehabilitation can take place in a special rehabilitation ward or hospital, at an outpatient facility or at home; depending on the needs and requirements of the patient and also the severity of the disabilities. The choice of location also depends on the facilities and personnel available in the community.

Therapists play an important role in rehabilitation (Sife 1998, Carr and Shepherd 2006, Johnstone 1976). They uniquely contribute to the motor control training based on a contemporary understanding of impairments, biomechanics, motor learning, exercises science and factors that influence brain reorganisation after injury. Their main aim is to revive motor performance in functional tasks. Learning motor skills involve two critical components particularly in the early stages of stroke (Adams 1991, Carr and Shepherd 2006). These are: identifying what is to be learned, and understanding the ways through which the goal can be accomplished. Therapists conduct different assessment tests, see Table 1.0 (Carr and Shepherd 2006) for analyzing the motor function of stroke patients that allow them to hypothesize about the cause of motor dysfunction and plan a treatment module accordingly.

The assessment tests follow the help of the therapists which are seen in setting achievable and meaningful goals which are aimed at improving specific skills of an individual. The goals have to be challenging but attainable. Therapists render feedback on any essential aspect of skill acquisition that learners receive about their performance of an action both intrinsic and augmented. Therapists also plays the role of a facilitator and teacher by assisting the individual in transferring learning from the rehabilitation setting, i.e., practice environment to everyday setting. Therapists also help an individual in practicing the acquired action during training which could be task specific (Magill 2001, Lee and Aronson 1974, Lundvik *et al.* 1999).

Sometimes when the individual faces difficulty in practicing a particular action due to muscle weakness and can only achieve that action through a huge compensation, the therapist help modify the task or the environment to reduce that compensation and hence the difficulty of the task whilst encouraging normal movement.

Over all the therapists plan and provide meaningful tasks for improving the skills of a stroke subject with sufficient intensity of meaningful exercise involved (Butefisch *et al*. 1995, Taub *et al*. 1993). The practice involves objects rather than abstracts (van Vliet *et al.* 1995, Wu *et al.* 2000).

2.4 Conclusion

The occurrence of stroke strikes an imbalance in the survivor's personal, professional and social environments. The causes leading to stroke need to be analyzed to plan a suitable treatment module for a victim. The subjects needing rehabilitation are provided with a therapeutic guideline and are transferred to a rehabilitation environment where physical and occupational therapists help them train their constrained movements. This helps the subjects regain their normal movement patterns over a period of time. Due to the insufficiency of intensity and innovation during training, the conventional therapy needs to be revolutionized with technological interventions. It could also be argued that feedback during training is one of the important factors in motor learning theory (Magill, 1998). Also, the use of technology driven methods has been widely used in the recent years to revolutionize the rehabilitation process (O'Dell, Lin *et al.* 2009). Technologies such as robotics, haptic interfaces, VR or combination of these has been used to provide therapists with more flexibility to speed up the rehabilitation process (Holden 2005; Lucca 2009; Reinkensmeyer 2009; Volpe, Huerta *et al.* 2009; Lo, Guarino *et al.* 2010). The second chapter starts with the favor of technologies used in present day rehabilitation scenarios and different other types of technologies in place with a critical evaluation of any clinical trials which has been conducted by any of the systems. A highlight of any promising systems in place which would further be available for testing on stroke patients is also outlined.

CHAPTER 3. Technological Interventions

Conventional therapy does not accommodate repetitions, exercise intensity, practice and precision in rehabilitation training all of which being the essential tools in the recovery process of stroke patients (Sunderland *et al.* 1992, Butefisch *et al.* 1995, Kwakkel *et al*. 1997, Van der Lee *et al*. 2001). It has been shown that the incorporation of technology alongside conventional therapy tends to increase the intensity of practice. It also increases the motivational gains by accelerating the rehabilitation process through engagement and entertainment of the subjects. These attributes increase the functional outcome through maximum effort of the user while performing the relevant tasks (Burridge *et al.* 2011). Some of the interventions which are already being used for the rehabilitation of the upper extremity post stroke are robots, virtual reality, motion sensing technology, haptics and glove technologies.

Robots were originally defined as a machine (sometimes resembling a human being in appearance) designed to function in place of living agents, especially one which carries out a variety of tasks automatically or with a minimum of external impulse (Capek, 1921). Robots can support and supply the simultaneous diagnosis and training of stroke patients even in the absence of a therapist and physicians. The use of robot-assisted therapy reduces the probability of profound labour involvement during the rehabilitation process. Robotic interventions attempt to improve and benefit conventional therapeutic measures and are being used as a diagnostic and therapeutic aid (Sietsema *et al.* 1993). It is believed that robot assisted therapy helps recover the hemiparetic arm better than the conventional therapy (Butefisch *et al*. 1995) with profound therapeutic benefits (Krebs *et al.* 1998, Lum *et al*. 1999, Lum *et al*. 2002, Prange *et al*. 2006).

Robots can facilitate rehabilitation tasks in order for the patients to regain the original motor function of the limb as well as take over functions in daily living (Rosati *et al.* 2009, Miller *et al*. 2009). The UK Stroke guidelines recommend *'Robot-assisted* *movement therapy should only be used as an adjunct to conventional therapy when the goal is to reduce arm impairment'* (Intercollegiate Stroke Working Party, 2008). Rehabilitation robots and assistive robots are the two branches of robotic systems. Rehabilitation robots are mainly used during the therapy periods in clinics where a large number of assistive robots are used as continual aids to the stroke patients. Rehabilitation robots can be classified by degrees of freedom, structure (end effector or exoskeletal), or location of use (a home or clinic based system).

The concept of the interactive robotic therapist was first coined in the late 1980s and it was in the early 90s when the first robot was developed for manipulation of the human arm, which was called the interactive robotic therapist (Hogan *et al.* 1992). The interactive robotic therapist allowed simultaneous diagnosis and training by therapist through interactions with the patient. Additionally, the physical or occupational therapist could control and manage the therapy process by operating a remotely located robotic device (August *et al*. 2005, Sanchez *et al*. 2006, Li and Song 2009).

3.1 Robotic Interventions

Following the success of 'the interactive robotic therapist' robot, several other rehabilitation robotic devices have since then been designed and developed. Some of them have been tested and the positive outcomes showcase a growing interest of the physicians, therapists and the researchers in this filed (Hogan *et al.* 1992, Burgar *et al.* 2000). This is due to the fact that in motor learning and practice requirements, robots can provide patients with: intense movement practice, continuous feedback and games (which if not considered as functional tasks, may be motivating or entertaining, a degree of independence during therapy and a record of progress).

Some of the current robots used in active rehabilitation are MIT-MANUS (Krebs *et al.* 1998), MIME (Mirror Image Motion Enabler robots) (Burgar *et al.* 2000) , ACT-3D (Yao *et al.* 2007), ARMin (Nef *et al.* 2006), ARM Guide (Assisted Rehabilitation and

Measurement) (Kahn *et al.* 2006), Bi-Manu-Track (Hesse *et al.* 2003), T-WREX (Housman *et al.* 2007), GENTLEs (Loureiro *et al.* 2003) and the NeReBot (Rossi *et al.* 2007), though the major findings in robot-mediated rehabilitation come from the MIT-MANUS robot (Hogan *et al.* 1992; Aisen *et al.* 1997, Rohrer *et al.* 2002) and the Palo Alto/VA Stanford Mirror Image Motion Enabler (MIME) (Burgar *et al.* 2000) which has undergone extensive clinical trials.

3.1.1 MIT-Manus

Talking of robotic manipulators this planar robotic manipulator is a 2 DOF device which aims at shoulder and elbow rehabilitation. This robotic device which targeted hemiplegic stroke rehabilitation was one of the first robotic devices to be developed. The rehabilitation of the shoulder and the elbow is achieved by assisting the subject's hand in a horizontal plane during a goal directed movement. Several visual, auditory and tactile feedbacks are provided during the execution of a task. This manipulator does not require any power while traversing the workspace with its end point manipulation. This allows the device to be used as an effective way of capturing motion. The evaluation and assessment of the movements during the trajectories followed in the workspace can be determined following a kinematic analysis (Hogan *et al.* 1995, Krebs 1998, O'Malley *et al*. 2006).

MIT-MANUS can safely move, guide, or resist the movement of the patient's shoulder and elbow. The MIT-MANUS also measures the position, velocity and forces on the end-effector. This data is fed into the PC updating the graphical user interface in real-time supporting the rehabilitation training with a game-like motivating environment. The graphical user interface thus provides the patients with more interactive end fun goals to achieve. The loading of the spatial module on to the end of the planer module of the robotic manipulator gives it a 3-dimensional range. This enables the patient to practice more diverse exercises and thus improves performance.

Krebs *et al.* (1998) reports a clinical trial with 20 stroke patients (follow-up trial after 3 years of the first trial) suffering from motor impairments of the upper limb using MIT-MANUS robot and information technology (VR environment). They reported that the improved outcome sustained over three years, the neuro-recovery process continued far beyond the commonly accepted 3 months post-stroke interval. They also concluded that the neuro-recovery was highly dependent on the lesion location.

Figure 3.1 MIT-MANUS Robot (Krebs *et al*. 2004)

Several other studies evaluating the effect of MIT-MANUS on chorinic hemiparesis have shown positive improvement in terms of better strength, reduced motor impairment and increased functional independence as compared to the conventional therapy (Finley *et al.* 2009, Kwakkel *et al.* 2008, Prange *et al.* 2006, Teasell *et al.* 2007).

3.1.2 ARM Guide

ARM Guide is a robotic device designed as a diagnostic tool for assessing movement impairment such as spasticity, muscle tone and coordination problems. It also acts as a therapeutic tool (active-assisted therapy) to treat hemiparetic arms. For the arms to slide the robot has the slides resting on a linear restrain strapped to a splint so that the motor activities could be performed along the bearing proving motor assists or resists (Reinkensmeyer *et al.* 2000). This device also acts as a therapeutic tool for arm rehabilitation providing effective assessment and evaluation in the process.

Figure 3.2 Arm Guide Rehabilitation Robot (Kahn *et al.* 2006)

During initial trials on three subjects the robotic device showed promising outcomes in terms of quantifiable benefits in the chronic cases of the hemiparetic arm (Reinkensmeyer *et al.* 2000).

3.1.3 NeReBot

It is also a cable robotic device aimed at providing rehabilitation to the upper extremity during the neurological conditions affecting its functions. Having seen the MIT MANUS robotic device which was a 2 DOF robotic manipulator NeReBot is a 3 DOF cable driven robot. The cables are attached to the upper extremity of the subject using a splint which is held by a frame that can be transferred from one location to another according to the need of the rehabilitation exercise. The robotic device is capable of passive or active assisted therapy. The length of the wire can be controlled allowing a flexible workspace to carry on the rehabilitation exercises (Rosati *et al.* 2005). Therapists help in planning a pre-set trajectory to work upon by the subjects. This was the subjects independently follow a teacher trajectory which would benefit their recovery from a motor deficit of the upper extremity.

Figure 3.3 NeRoBot (Neurorehabilitation Robot) for rehabilitation (Masiero *et al*. 2007)

The clinical trials with twelve patients undergoing training with NeReBot provided better motor recovery and improvements in the functional abilities of the patients than the patients taking conventional therapy (Rosati *et al.* 2007). This robotic therapy did not bring about any negative impact on the over all outcome. It has been concluded from the clinical trials of the cable driven robot that the rehabilitation of the upper extremity may be offered with a complimentary therapy option during post-stroke rehabilitation. It would provide a novel therapeutic strategy for neurological rehabilitation.

3.1.4 GENTLE/S

GENTLE/S is a robotic system which comprises of the 3 degrees-of-freedom haptic master robot arm and an overhead frame for supporting the patients arm and mounting the haptic master (Loureiro *et al.* 2003). This system was designed for the rehabilitation of the stroke patients using haptic interface technology. The use of the haptic technology allows the patient to work in a virtual environment and perform:

- Passive (the patient remains passive and the robot takes the patient's arm along a pre-defined movement path);
- Assisted (the patient initiates the movement and then the robot assists the patient in completing the task); and
- Active (the patient does most of the movement except for correcting forces from the robot) modes of robotic therapy.

The system also allows a non-resistive three dimensional arm movement. Depending on the patients choice of activities from the list of ADLs (activities of daily living such as drinking, eating, dressing, etc.), a customised choice of exercise program can be built..

Figure 3.4 GENTLE/S rehabilitation robot (Amirabdollahian *et al.* 2007)

This provides the patient a choice from different types of exercises with varying difficulty levels hence enhancing engagement and thus better recovery chances. Coote *et al.* (2008) report a clinical trial to evaluate the effectiveness of GENTLE/S therapy on twenty subjects with arm dysfunction (varying degrees of motor and sensory deficit) post-stroke

All the subjects were asked to carry out functional exercises with haptic and visual feedback from the system. The trial demonstrates positive results suggesting that the robot-mediated therapy can have greater treatment effects for the same duration of non-functional exercise.

3.1.5 ARMin

ARMin (Mihelj *et al.* 2006) was especially designed for neurological rehabilitation. It is a 6DOF robotic exoskeleton with 3DOF at the shoulder, 1DOF at the elbow, 1DOF at the forearm and 1DOF at the wrist allowing various combinations of proximal and distal arm training modes. It acts as a device therapy medium as well as a testing tool for the existing rehabilitation testing protocols. Movement therapy mode, game therapy mode and training mode are the three therapy modes of the ARMin exoskeleton.

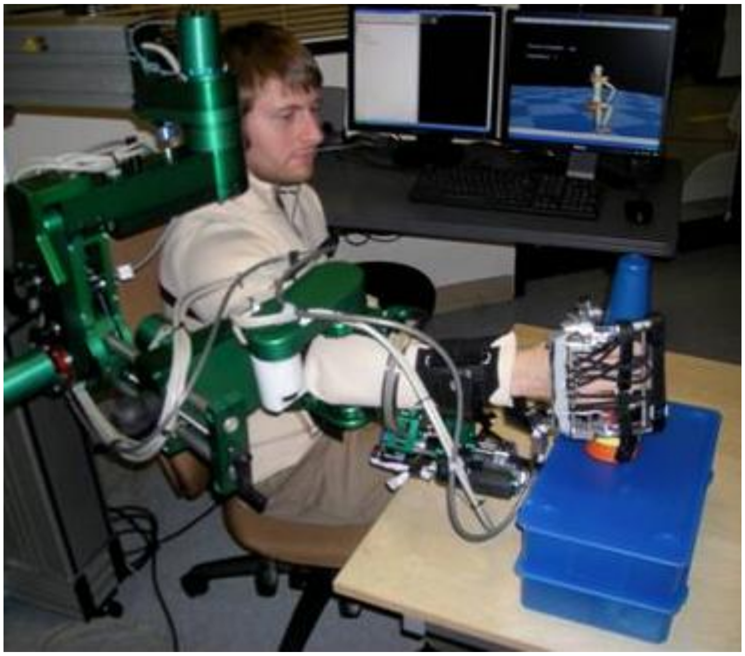

Figure 3.5 ARMIn Upper Extremity Robot (Mihelj *et al.* 2006)

In the movement therapy mode, the therapist guides the patient arm to form a particular trajectory which is repeated by the exoskeleton. In game therapy mode the patient is allowed to engage in simple gaming activity like a ball game. If the patient is able to play with the virtual ball, the ARMin simply compensates the weight and if not the ARMin guides the patient arms with an adjustable force towards the ball position. Finally, in the training mode the patient is trained with ADL tasks like eating or grasping an object. In this mode the patient generates the trajectory which is based on the patient arm position and speed alongside ARMin predicting the required forces and torques.

In ARMin II (Mihelj et al. 2007), there are 2 additional DOFs for the forearm in order to allow training of ADLs and an additional DOF to accommodate the vertical movement of the center of rotation of the shoulder joint. Thus the ARMin II allows more flexibility in terms of upper limb movement patterns during training with the ADLS.

3.1.6 ACT3D

Arm coordination Training 3-D (ACT3D) is a device that tackles undesired abnormal muscle coupling arising from the loss of independent joint control in the paretic upper limb (Sukal *et al.* 2007).

Figure 3.6 ACT3D robot for hand rehabilitation (Sukal *et al.* 2007)

It consists of a modified HapticMASTER robot with an instrumented end effector, integrated with a Biodex experimental chair.

The end effector is a 6DOF measurement device used to monitor forces and torques. An instrumented gimbal is used to record joint angles. HapticMASTER provides a frictionless, stiff haptic surface and imposes forces on the arm to either increase or decrease the amount of limb support required by the subject during a task involving reaching action. A rigid forearm hand orthosis is used to couple the arm directly to the robot. A virtual arm is rendered (using the OpenGL API) (Shreiner 2009) on the screen in front of the subject that provides online feedback about limb configuration and target location during experimental tasks. There is also the possibility of the auditory feedback when the end effectors of the device make contact with the haptic table during the task execution when the arm is required to stay above the surface.

3.1.7 T-WREX

The Therapy Wilmington Robotic Exoskeleton (T-WREX) is an anti-gravity arm orthosis robot (Housman *et al.* 2007, Sanchez *et al.* 2006). This was designed to enable an individual with significant arm weakness to achieve intense movement training without the expense of a supervising therapist. It was designed as a passive 5DOF body-powered device that contains no robotic actuators. This robotic exoskeleton provides a large 3D workspace enabling naturalistic movement across approximately 66% of the normal workspace of the arm in the vertical place and 72% in the horizontal plane (Sanchez et al. 2006).

The T-WREX also has a software module that provides a game-like virtual environment to practice functional arm movement. In the very beginning this robotic module utilized Java Therapy. Java therapy is resource centre which had the access to a library of different evaluation methods and therapy activities (Reinkensmeyer 2000).Haptic devices such as commercial force feedback joystick or a normal joystick can be used to interact with the therapy exercises downloaded from the resource centre (website). These force feedback devices help assist or resists the movements performed during the rehabilitation training.

Since Java therapy requires internet connection, it limits its use to home-based rehabilitation practices. The T-WREX researchers have developed a custom, upgraded software model called ‘Vu Therapy’ that has overcome the limitations of Java Therapy. They have also customised it to game design for mimicking functional arm movements. It provides training in a simple virtual reality environment. Auditory and Visual feedback is provided throughout the game play.

T-WREX enables individuals with severe movement impairments to practice intense, repetitive and simulated tasks. Such practice reduces motor impairment and improves motor function. The study by the researchers illustrates the safe use of the T-WREX system to retain the arm movement in the clinical setting with minimal therapist assistance.

3.2 Virtual Reality Intervention

Virtual reality provides an opportunity to people suffering from motor disabilities after a stroke to practice everyday activities in a computer-simulated environment which cannot be practiced in a home or within the hospital environment. The advent of gaming features and interactive virtual environments helps attract the user to spend ample time in carrying the practice in a virtual setting with increased motivation.

The term Virtual Reality (VR) was coined in the early 1980s by Jaron Lanier, who founded VPL research, the first company to sell VR products (Boden 2006). Before that, VR was described as "artificial reality", "cyberspace" or "virtual worlds". VR is the result of the evolution of computers from a utilitarian instrument that was used to make numerical computations to a machine that could adapt to the user's cues to create an almost lifelike experience. Generally, VR is the term that is used to describe computer-simulated environments that can reconstruct real world environments as well as imaginary worlds. VR is often used to describe the wide variety of applications commonly associated with immersive, highly visual, 3D environments. Virtual reality could be defined as the amalgamation of the computer hardware and software used to produce a simulation of the real world objects and events (Weiss 2006). This encourages the user to immerse oneself during the interaction with such environments. Nevertheless, nowadays VR experiences are supported not only by realistic immersive graphics but also by means of sound and/or haptic/force-feedback systems. Although VR has been popularized as a new form of entertainment, it has additional applications in areas as diverse as business, industry and medicine.

Currently, several VR systems and methods have been developed for motor rehabilitation of the upper extremities following strokes based on different paradigms and hypotheses. In this section a number of studies that explore the different aspects of VR based rehabilitation methods will be reviewed.

The effectiveness of repetitive task training has been concluded by some of the studies to improve the motor skills and cognitions (French 2007). Virtual reality has established itself to be a self operated training platform that increases the possibilities of intensified repetitions of the functional task which could be performed within a hospital environment under the guidance of a therapist (Kwakkel 2004; Merians 2002). With the technological revolution and ease of accessibility, virtual reality is finding its way in to the rehabilitative setting more and more (Budrea 2003). Still the use of virtual reality has not shown a common trend in the clinical setting. Though with the increased burden on the physical and occupational therapists to provide rehabilitation to stroke survivors, there is a need for a training platform which could be low-cost. A comprehensive prevalence of game-like systems has been alluring researchers and clinicians to turn them into a module for virtual reality based rehabilitation systems (Burdea 2003, Deutsch 2008; Rand 2008). These systems have shown to have therapeutic inclinations apart from the obvious recreational gaming provisions. There is evidence of interactive video gaming systems being designed for virtual reality based rehabilitation (Lang 2010).

3.2.1 Virtual reality Components

Apart from the presence of the user and the virtual reality engine the interactivity in the virtual environment has to be controlled by several other peripherals (Weiss 2006). Virtual reality has mainly three components, input devices, display systems and output devices. The primary input devices could be summed up as 3D pointing devices which include a 3D mouse or 3D digitizer, whole hand inputs which include data gloves or gravity balancing robotic exoskeletons. The primary input devices could also include the whole body input such as the NASA suit-based device developed for the purpose of studying whole body biomechanics during the space mission.

Along with these primary inputs in the virtual environments there are other devices which are used to track motions of the human limbs to facilitate the effective interaction with virtual environments with ease. There are different principles on which tracking devices are based and manufactured. A tracking device could be electromagnetic, mechanical, optical acoustic (ultrasound) or inertial.

The output devices of virtual reality constitute of visual displays, auditory interfaces, haptic interfaces, motion devices and olfactory interfaces. The types of visual displays are:

- Head mounted displays (HMDs)
- Boom mounted displays
- Stereoscopic displays
- Projectors or computer screens

Virtual Reality can be immersive or non-immersive (Stone 1995) or it can be desktop, projection or immersive (Sanchez -Vives *et al.* 2005). The head mounted displays are used in the development of immersive virtual reality systems. Fully immersive VR systems can consist of a head-mounted display (HMD), a computer augmented virtual environment (CAVE) or a large screen, which curves to some extent towards the participants producing a wide-angle view (Cruz-Neira *et al.* 1992, Bowman *et al.* 2001). The form of virtual environments simulated on a conventional computer is termed as non-immersive (Sisto *et al.* 2002). Thus, in virtual rehabilitation virtual environments or objects cater to the user a visual feedback which could either be accessed through the head mounted displays or on a computer screen. Other input devices mentioned above also provide the user feedback such as motion, touch, balance or hearing (Weiss 2006). Depending upon the single limb tracking or the full body movement tracking the interaction of the user during a physical activity could be either inactive or highly active. For example, if a user is interacting with the virtual environment with the use of a input device such as a data glove, his/her physical activity could well be less active compared to a user wearing a full body tracking suit and performing the physical activity with full body interaction. The resolution, accuracy and system responsiveness determine the quality of interaction of the user with the virtual environment. Hence the software and hardware components of a virtual reality system determine the essence of conciliation of the user and the virtual environment (Greenleaf 1994).

Virtual reality revolves around immersion, interaction and imagination (Burdea and Coiffet 2003). Immersion could be defined as the sense of existence in the virtual environment during a physical activity rather than into a real world and this could depend on the efficiency of the software and hardware (Weiss 2006). Immersion or presence can also be regarded as the amount of power with which the attention of the user is focused on the task at hand (Witmer *et al.* 1998). When a user relates him or her to the virtual environment they are interacting with, a sense of presence could be accommodated to their being (Schuemie 2001). In the Virtual environment users can interact as well as navigate through these simulations which can also be updated in real time (Rose *et al.* 1996, Rizzo *et al.* 1998, Riva 2002, Tarr *et al.* 2002, Riva 2005, Thompson *et al.* 2009, Zhao and Xu 2009).

Some of the studies have shown growing prospects of the use of virtual reality in neurological rehabilitation. Both in upper extremity (Hendrson 2007) and lower extremity (Deutsch 2011), functions are shown to have improved over time with the use of virtual reality. Studies reported that cognition, perception and functional tasks improved upon the use of virtual reality based rehabilitation (Rose 2005).

3.2.2 Virtual Reality Prospects

The execution of rehabilitation tasks for better therapeutic outcomes requires quantified repetitions and measured goal-oriented tasks both of which are important for improved neurological rehabilitation (Dobkin 2004). Training provided in an augmented environment accelerates the better recovery in functional tasks (Risedal 2002). New skills could be learned for better use of the constrained movements during the rehabilitation practice. Task specific training in the virtual environment has shown positive results in cortical reorganization (Nudo 1996; Nudo 2001) and behavioral change (Dean 1997) in both humans and animals.

3.2.3 Virtual Reality Based Upper Extremity Rehabilitation

Several psychosocial interventions have seen the use of VR technology for decades but it was in the early 90s when VR started being tested successfully as a means for assistive rehabilitation such as evaluating the need of an individual with motor disability. Clinicians and physiotherapists started setting up the trend for the use of virtual reality technology in physical rehabilitation (Greenleaf *et al.* 1994, Kuhlen *et al.* 1995, Rose *et al.* 1996b). Ever since then the technology has found its prominence as a potential tool in the field of post stroke rehabilitation research. There is an ever growing use of VR technology as an assessment and treatment tool in rehabilitation (Rizzo *et al.* 2005, Burdea *et al.* 2003, Rand *et al.* 2005, and Weiss *et al.* 2006, Pareto *et al.* 2008, O'Dell *et al.* 2009).

Clinicians have been lured to the strengths and attributes of VR technology to apply this in the field of physical rehabilitation (Burdea *et al.* 2003, Rizzo *et al.* 2004). It provides recreational opportunities for people with severe disabilities (Wiess *et al.* 2003), people with cognitive (Rizzo 2002, Zhang *et al.* 2001, Grealy *et al.* 1999, Lewis-Brooks 2004, Weiss *et al.* 2003, Wallach *et al.* 2009) and people with motor deficits (Kiznoy *et al.* 2003, Sveistrup *et al.* 2003, Merians *et al.* 2002, Henderson *et al.* 2007, Kim *et al.* 2009, O'Dell *et al.* 2009).

It also shows promise for training subjects in their activities of daily living with an individualized virtual environment such as VR simulation of kitchens, a vending machine, letter posting etc. (Davies *et al.* 2002, Gourlay *et al.* 2000 , Schultheis *et al.* 2000, Pareto *et al.* 2008, O'Dell *et al.* 2009).

The rehabilitation of driving skills following traumatic brain injury is one example in which individuals may begin at a simple level (straight, non populated road and driving) (Rizzo *et al.* 2002, Burdea *et al.* 1994). Another example of this includes the children with cerebral palsy, who have used VR training for spatial awareness and to learn to operate motorised wheelchairs. Harrison *et al.* 2002 studied six subjects with severe impairments testing them in VR by navigating powered wheelchairs. The research has shown the clinical suitability of the use of VE in rehabilitation.

Lewis-Brooks (2004) reported the testing of a system which allows post-stroke patient limb movements and body posture to be tracked while at home and converted into "pleasant", abstract images and a melody. Five post-stroke patients who had suffered a stroke between two and seven years previously and received therapy from zero to four years were selected and tested. The training tasks were ADL independent and the rehabilitation process was supervised by a physiotherapist. The study illustrated increased activity by the use of the system, improvement in function and motivation in the patients, the technical and clinical suitability and its positive impact on the rehabilitative process as a whole.

However the five participants, all positive in the interviews were pointed as insignificant in number for a research study and the loose methodology implemented in the sessions was reported as inconclusive to the level of a convincing scientific result. They also concluded that the limited time frame of sessions with such a diverse group was also a restriction.

Researchers at the MIT and Harvard Medical School as described by Holden *et al.* (2005, 2007) used a telerehabilitation system where the patient interacts with a PC-based virtual environment to perform therapeutic exercises remotely. The system consists of three sets of exercises: posting a letter in a letterbox (a reach-to-workspace exercise), pulling up the sleeve of a garment (a hand-to-body exercise) and a repetitive pronation/supination exercise (reciprocal movements and grasp-release exercises). The patient follows as closely as possible the trajectories of the physiotherapist's movements, which are pre-recorded, and an error-based score is provided after each exercise to provide knowledge of results. Velocity, orientation and rotation of the subject's movements are measured and the system also allows the remotely located therapist interacting with audio visual conferencing to alter the parameters of the exercises as appropriate. Apart from some technical problems reported, the research offered useful, quantifiable information about their methods and analysis.

According to Holden *et al.* (2007) eleven subjects were provided training which involved imitation of a movements taught by the remote therapist with visual guides, while the subject's arm, hand and finger movements were tracked using a commercially available P5 glove. The study concluded that each subject made significant improvements and was able to generalize on their virtual reality (VR) training to real world performance.

Crosbie *et al.* (2004) have tested the possibility of virtual reality (VR) for the rehabilitation of subjects with upper limb disabilities. The system aimed at the reach, grasp, release and manipulation of the components at a range of levels of difficulty according to the patient's therapeutic requirements. The system consisted of a non-immersive VR simulating a domestic space and an avatarial arm and hand. The user had to wear a head-mounted display and a data glove to interact with the virtual environment. Visual and auditory cues were given as the user interacted with simple, geometric shapes within the environment. Magnetic sensors were attached to the shoulder, elbow and wrist and the HMD (head-mounted display) to ensure that correct posture was maintained. Apart from the subjects getting tired, they were likely to immerse in the virtual environment and reported a favorable experience whilst using the system.

3.2.4 VR games in Upper Extremity Rehabilitation

Rehabilitation tasks can be made more motivating and effective with a repetitive series of cognitive or physical challenges (Rizzo and Kim 2005). These challenges can be achieved with a goal-reward structure within a user defined or predefined interactive and graphic-rich series of virtual games (Burke 2009). Gaming features in the virtual environment sought to enhance training and motivation in the people undergoing physical and occupational rehabilitation (Gotsis 2009, Jack *et al.* 2001, Kizony *et al.* 2003, Phelps *et al.* 2009).

Several virtual games such as moving a circle or sphere around a target, picking up balls and placing them with other balls and pushing a box were simple but now VR games can be made more complex by displaying a whole new world. For example, Nearlife, Inc. has created a Virtual FishTank to allow people to create and release their own digital fish into a virtual aquarium and interact with their own fish via motion sensitive cameras (Gehringer 2002). These virtual reality-based games, like systems use motion sensors as the user's input to the VR and provide flexibility of training the stroke patients; this is done with a variety of activities that aim at training their movement dexterity and fine motor control.

There are several other games that can push the stroke patients harder in the recovery process during therapy. Researchers at the Rutgers University have developed a video game modified from XBox console that helps patients with stroke rehabilitation. Doctors at the Northern Arm and Hand Centre are making use of 10 different computer games for arm and hand therapy. There are other console games like Wii Boxing to plan movements and hand eye coordination, Trauma Centre (Wii game) for stroke patients to fine tune their motor skills, Wii Golf require patients to think spatially and control movements, Cooking Mama helps patient to fine tune their motor skills, Wii Tennis is excellent for arm training and Guitar Hero helps patients in coordinating and improving hand function (Clark *et al.* 2010, Mouawad *et al.* 2011, Saposnik *et al.* 2010). There are other devices that can make physical therapy more fun and effective like EyeToy (for improving physical activity and interaction) and Bodypad (integrates motion capture of the whole body) which make physical gaming more interactive (Yavuzer *et al.* 2008, Rand *et al.* 2008, McLaughlin *et al.* 2005). Several other games have been developed especially for Virtual reality applications. These include IREX, which has proven effective for children with cerebral palsy (Bryaton *et al.* 2006); the Computer Assisted Rehabilitation Environment developed in Israel, which helps paralysed patient put atrophied muscle to work by simulating ADLs or virtual sports; VR Rehab developed by Human-Machine Interface at Rutgers which immerses patients into the game and allows them to manipulate onscreen objects and characters; and Virtual Reality Robotics developed at the Rice University, which uses joystick and virtual reality that helps patients improve hand eye coordination (Burdear *et al.* 2002, O'Malley *et al.* 2006).

Although these aforementioned games like virtual reality training systems are effective they do not provide whole arm and hand assessment and rehabilitation. Moreover, they require a clinical setting for the rehabilitation process, are bulky, expensive and cannot be used in home environment. Thus there is still a need for a more advanced system that could be easy to use and can be affordable for home use providing a safe and interactive assessment and training environment.

Therapeutic game-like virtual environments including a touch sensitive ball game, a goal keeping game and snowboarding game have been developed at the University of Haifa, Department of occupational therapy (Kizony *et al.* 2003, 2004). This was all designed with the aim of providing cognitive and motor training for a range of neurological conditions. The games were tested on 14 subjects differing in age, ability levels and with different clinical conditions. There are several advantages of using this game: the system uses specific body parts or all body parts, the user can view through the video instead of viewing through the avatar (the virtual presence of the user or the user’s limb), the direct control of the movement by the user, and the user does not need to wear a head mounted display (HMD), data glove or other external device. The game could have been made more effective with the use of three dimensional visual feedbacks.

Jang *et al.* 2005 report a non-immersive, video-game like, virtual rehabilitation system similar to that developed at the University of Haifa. The researchers sought to study the impact of virtual reality on motor cortical organisation of stroke patients. Ten patients who could move their elbow against gravity were tested 6 months post stroke. The patients were tested with a set of ADLs in the virtual reality system. The sensory feedback received by the patients during the training with this video-game was that the virtual trainer was able to internalize the motor representation of the target motor behaviour (set by the therapist) through imitation of the taught trajectories by the physiotherapist.

3.3 Haptics and Virtual Reality Rehabilitation

Virtual reality rehabilitation applications primarily use visual and auditory sensory input while haptic feedback and its use in rehabilitation have been limited due to technical reasons. Haptic interface devices provide users with a sense of touch and allow the user to feel a variety of texture as well as changes in texture.

3.3.1 Rutgers Master Glove

Rutgers Master glove is a compact haptic interface that consists of a cyber glove and the force feedback RMII glove (Jack *et al.* 2001, Boian *et al.* 2002). This exoskeleton device applies force to user's fingertips and uses non-contact sensors to measure the fingertip position in relation to the palm. The electronic device is connected to the VR simulation exercises (in the form of computer game) and a database running on a PC. Each exercise was used to train a single hand parameter, range, speed, fractionation (independent control of individual muscles via direct input from corticospinal tract) and strength. The Cyber glove was used for exercising range of motion, speed, fractionation of movement and the RMII force feedback glove for finger strengthening. RMII has been tested with patients suffering from chronic hemiplegia and they are reported to have gained significant improvement in several parameters of hand function (for example range of motion, speed, strength, etc.) (Kuttuva *et al.* 2006).

3.3.2 PHANTOM Device

This device was introduced by SensAble Technologies in 1993 which interacted with the computer and had force feedback capabilities (Salisbury 1999). It was an electromechanical device that was capable of exerting a force to the hands of the user while interacting with virtual objects on the computer similar to a real situation while interacting with a physical object. It was moreover a mechanical arm supporting a stylus or a thimble. A user can either insert his/her finger in to the thimble and manipulate a virtual object in the virtual scene present on the PC or manipulate it via the stylus. While the user is interacting with the virtual scene the device track the motion and position of the user's finger tip in the mean time apply forces on the user's fingertips. This haptic interface mechanism (PHANTOM) also allows multiple interactions with the virtual scene at the same time (Massie 1994).

Researchers from Slovenia (Bardorfer *et al.* 2001) used a PHANTOM device for the functional assessment of the upper limb movement capabilities. Patients could interact, explore and feel the specially designed VE via the Phantom Premium 1.5 allowing their three senses (sight, hearing and touch) in engaging and generating an effective outcome. The tests ranged from tracking tasks, assessment tasks for speed and accuracy and the measurement of maximal force capacity of the upper limb. The patients were asked to follow the circular and the Labyrinth (an intricate structure of interconnecting passages) trajectory holding the device. The tests have provided repeatable, quantitative and objective results claiming the suitability of the method and effectiveness of virtual environment (VE).

Broeren *et al.* (2002) identified a method to record quantitative measures of arm movements in a 3D virtual environment. Broeren *et al.* (2006) report on their research into virtual reality and haptics systems which was adapted to be used as movement training following stroke. They performed three tests starting with the Purdue pegboard dexterity test (measuring unilateral and bilateral dexterity for gross movements of hands, fingers and arms and finger dexterity) for fine motor dexterity and coordination and the dynamometer hand-grip strength. A third test for the upper extremity involved moving a

PHANTOM haptic device to various targets as part of a game varying the speed with respect of the target motion. The training involved the affected upper extremity in performing several ADL tasks and reported improvement of the paretic arm.

Conner *et al.* (2002) used an approach for rehabilitation of cognitive deficits following stroke using haptic-guided errorless learning with an active force feedback joystick and computer. In a study by Viau (2004), a VR task was validated as a tool for studying arm movement in healthy and stroke subjects by comparing the movement kinematics in a virtual environment and in the real world. Baheux and colleagues (2006) developed a 3D haptic virtual reality system to diagnose visuospatial neglect. Kim *et al.* (2004, 2007) designed a VR system to assess and train right hemisphere stroke subjects. The aforementioned researchers have concluded the use of haptics in the improvement in the upper extremity motor disabilities.

3.4 Data Gloves

These are the electronic gloves used to interact with the objects on the computer screen while manipulating the physical objects in the scene. Some data gloves have force feedback capabilities and some doesn't. Most of the data gloves consist of sensors and other electronic equipments on board to process the information while executing a task. Earliest recorded research on data gloves came in to existent in the 1970's when the task at hand was to analyse the hand gestures. The first physical product developed was by Zimmerman in 1982. The earlier version of the data gloves consisted to thin plastic tubes woven on a cloth and light sources and detectors to record the joint angles. With the advancement in technology fibre optics came in to use for the development of data gloves. The first fibre optic data glove was developed and commercialised by Visual Programming Language Research, Inc. this data glove consisted of sensors ranging from five to fifteen. Most of the data gloves consisted of flex sensors which simultaneously measured the joint angles of the fingers and the thumb. Some of the features which were added to these data gloves were the inclusion of the abduction/adduction sensors to measure the angles between the adjacent fingers.

As the use of the data gloves found wider applications a low cost version was developed in order for them to be accessible for research and development. In 1989 Mattel Intellivision developed a Power glove which would control the Nitendo video game console popular in the gaming industry at that time (LaViola 1999, Eglowstein 1990, Gardner 1989). The Power glove consisted of resistive ink printed on flexible plastic bends. These plastic bends imitated finger movements in order to measure the flexion of the thumb, index, middle and ring finger subsequently.

Figure 3.7 Data Gloves used in Virtual Reality Based Upper Extremity Rehabilitation (Cyber Glove 2009, 5DT 2005, P5 Glove 1986)

The Super Glove (LaViola 1999) was developed and commercialized by Nissho Electronics in 1995. It came with 10–16 sensors and used resistive ink printed on boards sewn on the glove cloth. An updated version of the Power Glove, the P5 Glove, was commercialized by Essential Reality, LLC, in 2002 (http://www.essentialreality.com.)

The Data Glove-like systems also include the commercial Space Glove, CyberGlove, Humanglove, 5DT Data Glove, TCAS Glove, and the more recent StrinGlove and Didjiglove as well as prototypes developed by research laboratories around the globe, such as the TUB-Sensor glove (Hofmann and Henz 1995, Hofmann 1998, Karlsson *et al.* 1998). Despite the differences in sensor technology, location and mounting, all the data gloves share the same design concept:

- Measuring finger joint bending
- Use of cloth for supporting sensor
- Meant to be general purpose device

As worn by the users the data gloves record data related to their hand configuration/motion. This data can be further used for hand and finger rehabilitation through dedicated exercises for finger range of motion, speed and fractionation.

The data glove used in our application is the one which uses bend sensor technology. Bend sensors are usually used to measure the bend angle. Bend sensors could either be conductive ink based, fibre-optic, or conductive fabric/thread/polymer-based.

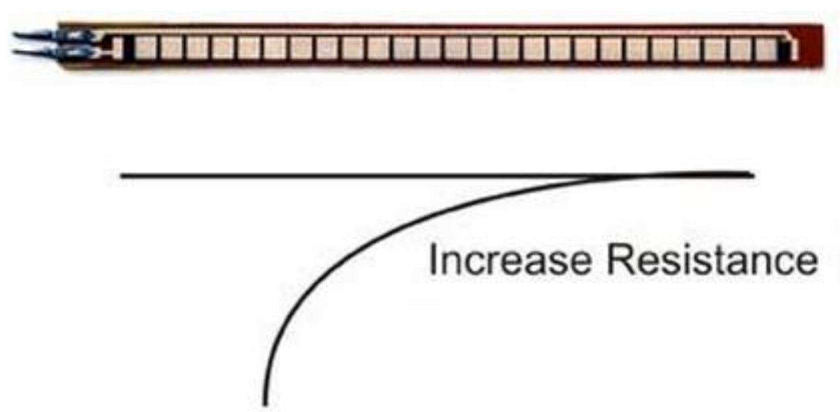

Figure 3.8 Bend Sensors Characteristics (Scientif Instruments, 2011**)**

Usually bend sensors make use of the material deformation properties where the change in resistance is measured at the time of sensor bend (Sensors, 2008). When the sensors are not flexed it attains resistance of 10Kohm and depending upon the degree of flex the resistance may vary between 10-40Kohm. When the sensors experience maximum bend of 90°, resistance reaches the range of 30-40Kohm. The sensor measures $\frac{1}{4}$ inch wide, $4\frac{1}{2}$ inches long and only .019 inches thick Figure 3.8.

For our applications VHand 2 from DGTech Technologies, Italy was considered, for its low cost and ease of integration into virtual reality application.

Figure 3.9: VHand for measuring Finger Movement (DGTech VHand 2007)

The VHand 2 glove is provided with five accurate bend sensors (10 bit resolution each) in order to sample minimum finger movements Figure 3.9. Flexpoint bend sensors are used to measure the finger movements. The sensor also consists of accelerometer to sense the hand movements in terms of the roll, pitch and yaw of the wrist. Since the MTx sensors from the Xsens Technologies are used to provide the location of the wrist during 3D motion, the use of the accelerometer output from the Vhand has not been considered.

3.5 Conclusion

It could be argued from the literature that technological interventions have revolutionized the field of research concerning upper extremity rehabilitation. Especially the integration of virtual reality with the existing technologies such as motion sensing technology has seen a leap in providing upper extremity rehabilitation. Glove based systems have also found a way in reaching to stroke survivors with hand and finger disabilities. Exercise and practice, provided under the constant and repetitive watch of technology has enabled therapists to supervise more and more stroke patients in minimal time.

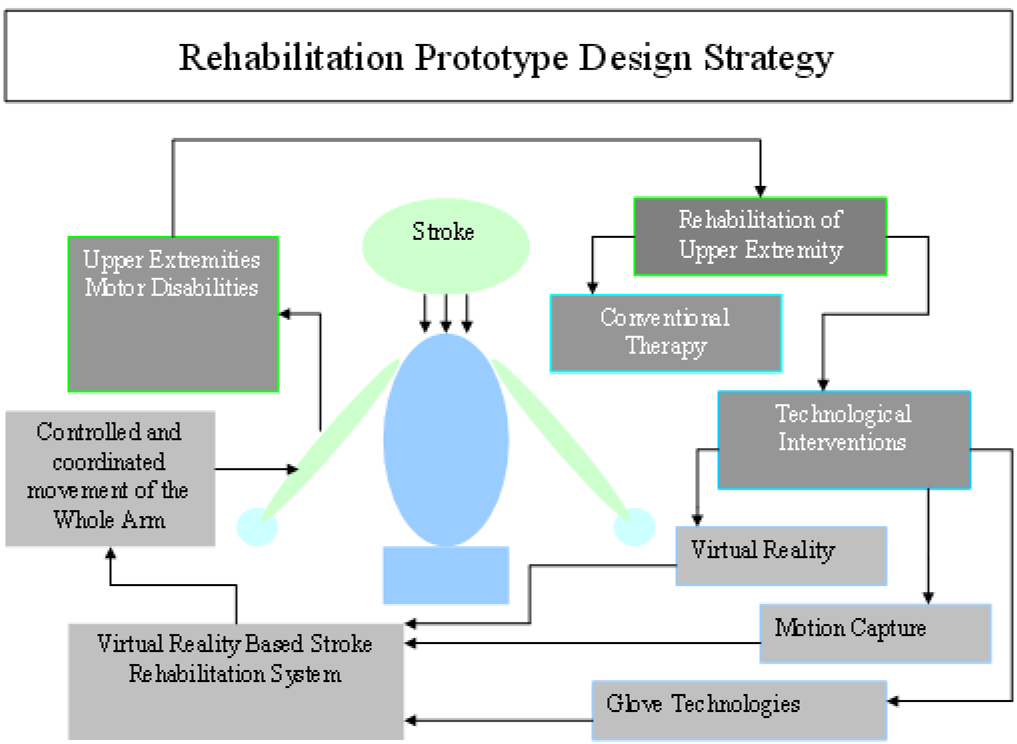

Figure 3.10: Approach to the VR-based UE system Design

Though researchers have successfully shared the burden of therapists through technological interventions, there is still a lack of a plethora of systems for rehabilitation of stroke subjects in their home environments. This would enhance the chances of better recovery and increasingly reduce the hospital visits of the stroke patients. Subsequently this would in turn lessen the economic burden on the related organization and also individuals striving for benefits linked to stroke survivors with upper extremity motor deficits.

The VR-based stroke rehabilitation system which this research aims to deliver targets an approach which would imbibe the existing motion sensing technology and glove-based hand and finger data acquisition technologies to design, develop and test its feasibility for stroke rehabilitation.

The overall approach is described in Figure 3.10.It could be seen that stroke affects the motor functions of the upper extremities which require immediate attention from the rehabilitation perspective. Clinicians and therapists use conventional therapy to facilitate a rehabilitation program which best suits an individual for better recovery. Technological interventions come as a help in assisting a therapist to design better strategies in less time and aimed at better outcome.

This also requires less vigilance on the part of the stroke survivors. Keeping in mind the cost involved in the technology, a less expensive and robust system is always a priority for an organization or individuals aiming recovery after stroke. Thus, our system encompasses the motion sensing technology and glove technology embracing virtual reality as the main target in the design of a VR-based upper extremity stroke rehabilitation system. A feasibility testing on healthy volunteers has been sought for in order to establish the suitability of the system both in the clinical setting and also home environment.

CHAPTER 4. Motion Sensors and Reference System Design

Over the last few years there has been an increase in the use of portable systems for estimation of human motion during rehabilitation (Yang *et al.* 2010). Micro-Electro-Mechanical Systems or MEMS have found their way to a wide range of such applications (Alaqtash *et al.* 2011, Bonato 2003, Kemp *et al.* 1998, Luinge 2002, Malzahn *et al.* 2011). It is a technology which in the most general terms can be defined as miniaturized mechanical and electro-mechanical elements (i. e., device or structures) that are made using the techniques of micro-fabrication. With their added advantage of being small in size (ranging from 1 micron to several millimetres), they can be worn on the body. MEMS consisting of sensors work on the principles of inertia which enables orientation measurement of human joint poses (Stilson, 1996).

4.1 Inertial Measurement Systems

A sensor which consists of a 3 axis accelerometer, 3 axis gyroscopes mounted in sensor housing at one point is called an inertial measurement unit (IMU). Inertial measurement unit measures the angular velocity and acceleration in three dimensions. It also measures the gravity with respect to the sensor housing. With respect to the position and orientation of the IMU the kinematics could easily be determined. The angular orientation could be obtained from the gyroscope on board the IMU and this information could further be used to subtract gravity from the accelerometer output to obtain the resulting acceleration. Position could be directly obtained from the double integration of the acceleration output from the accelerometer on board the IMU. Because of the integration drift problem (small errors in measurement of acceleration and angular velocity which is compounded in to larger errors in velocity and hence position estimate errors) the 3D orientation and position which is obtained from the gyroscope and accelerometer on board suffer from inaccurate estimate of position and orientation.

During the selection of the motion sensors for motion estimation of the upper limb, possible discrete attributes such as accuracy, portability, low cost, real-time interface and measurement of dynamic data, and clinical suitability, has been considered Figure 4.1. The clinical suitability of a human motion measurement system is described as its sensitivity, resolution and measurement range. The required accuracy for a normal human motion measurement system has to be close to 1° of static and 2°RMS of dynamics accuracy. Alongside the attributes discussed above, motion sensors from Xsens technologies possess electromagnetic capability and have proven standard for medical environments as well as it comply with the safety requirements for electrical equipment for measurement, control and laboratory use. These sensors are also easy to be integrated on a Windows platform and provide 3D orientation, 3D rate of turn, 3D acceleration, 3D magnetic field strength and temperature. Hence the MTx sensors from Xsens technologies have been chosen in our research. Two state-of-art inertial measurement units (IMU's) have been used which are commercially available from Xsens technologies (Xsens, 2008).

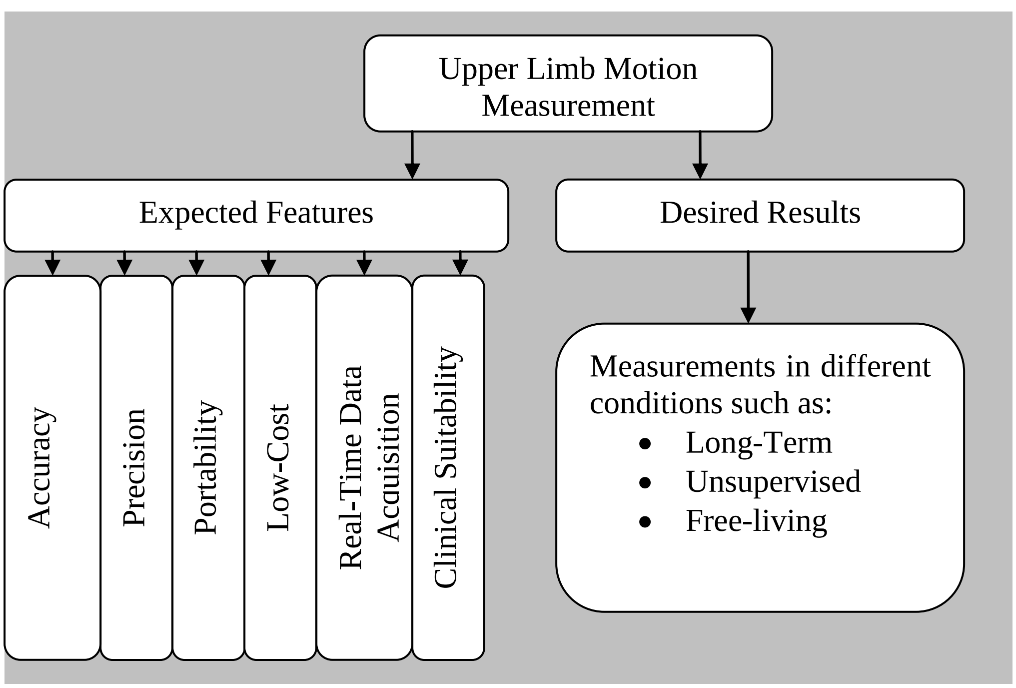

Figure 4.1: Attributes of a Motion Measurement System for Human Motion Analysis

Each IMU is a “9-degree-of-freedom (DOF)” solid-state motion sensor, or, a miniature gyro-enhanced MARG (Magnetic, Angular Rate, Gravity) system that provides drift-free three dimensional orientations as well as calibrated 3 DOF linear accelerations (from micro accelerometers) (Xsens, 2008). They also provide 3 DOF angular velocity (from micro gyroscopes) and 3 DOF magnetic field data (from micro magnetometers). The sensors compensate for the drift errors resulting from temperature effects on the integration of the angular velocity data by using accelerometer and magnetometer measurements, and have singularity free orientation output.

4.2 Working Principle of Inertial Sensors

The primary components of the inertial measurement units are accelerometers, gyroscopes and magnetometers. The gyroscope triad is an important part of the inertial measurement unit which acts upon the accuracy of the inertial measurement system. The rate of turn is measured by the gyroscope which entails information about the change in orientation. Drift is a common problem of gyroscopes which need to be referenced by other components in the inertial measurement systems. In the case of an attitude and heading referenced systems (AHRS), sensors such as the accelerometers are used to compensate for the attitude (roll/pitch) and magnetometers for heading (yaw). Thus these three signals from the gyroscopes, accelerometers and the magnetometers are combined in a Kalman filter (Kalman 1960, Kalman and Bucy 1961) and the resulting output provides an absolute 3D orientation.

4.2.1 Accelerometers

Acceleration is detected using the inertial measurement systems (IMU’s). Single integration of acceleration gives velocity which on further integration facilitates position along the accelerometer’s sensitive axis. Accelerometers could be divided in different categories depending on the requirement of sensitive axes along which the acceleration has to be measured. A single axes accelerometer or a tri axis accelerometer. A single axis accelerometer is made up of a mass which is suspended by a spring

Figure 4.2 (Luinge 2002). From the Figure 4.2, d is the displacement in the sensitive axis n , a is the acceleration and g is the acceleration due to gravity. For the rigid bodies situated in three dimensional space 6 degrees of freedom are required which would need 3 sensitive axes standing perpendicular to each other.

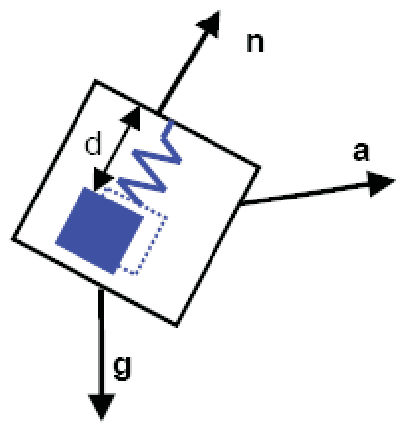

Figure 4.2A single axis accelerometer (Luinge 2002)

Hooke’s law governs the mathematical interpretation of a mass suspended by a spring. When a mass is suspended by a spring the spring exerts a restoring force which is proportional to the amount expansion or compression. This could be shown by the following equation:

$$F = -kd \qquad (1),$$

where k (Hooke's constant) is the constant of proportionality between displacement d and force F . Implying Newton’s second law of motion the mass suspended by the spring experiences a force which is accelerated in the direction of compression or expansion described as:

$$F = ma \text{------------- } (2)$$

This force brings compression or expansion to the spring in the direction of the force. Hence from equation (1) and (2):

$$F = ma = kd \text{ ------------- (3)}$$

So, from equation (3) the displacement could be derived as

$$d = \frac{ma}{k} \text{ ----------------------- (4)}$$

Which shows the mass is displaced by that amount upon the application of a force during the compression and expansion of the spring in the direction in which the sensor is accelerated. Similarly if displacement of x is caused, the mass undergoes an acceleration of

$$a = \frac{kd}{m} \text{ --------------------- (5)}$$

There upon in order to measure the acceleration, displacement of the mass connected to the spring is measured.

MEMS accelerometer converts motion to electrical energy. When a mass is suspended by a spring, forces affect this mass. The forces cause the mass to be deflected from its nominal position. The deflection of the mass is sensed as the change in capacitance.

In earlier studies it has been shown that along with the measurement of linear acceleration and vibration measurement of a moving object (Doscher 2007), accelerometers could also measure inclination which would further be utilized in measuring orientation in human motion analysis (Kurata *et al.* 1998). In our study we are measuring the 3D orientation of the upper extremity. Hence we would need a 3 axis accelerometer, thus a single axes accelerometer need to be duplicated along the other two axes. The use of MT9 sensors from Xsens solves the problem of 3D orientation estimation by using a 3 axes accelerometer on board the inertial measurement unit.

4.2.2 Gyroscopes

The inertial sensors from Xsens technologies consist of a gyroscope on board of the inertial measurement unit (IMU). Angular motion is measured using a gyroscope. Gyroscopes could be classified in to two broad categories, mechanical gyroscopes and optical gyroscopes. There are different types of gyroscopes available such as laser gyroscopes, spinning motor gyroscopes Figure 4.3, and piezoelectric based vibrating mass gyroscopes (H.R., 1995).

Conservation of angular momentum is the basis of mechanical gyroscopes. The sensitivity to the direction of angular momentum encompasses the working principle of gyroscopes. According to the Newton's second law of motion a body in angular momentum would remain in that state until and unless acted upon by an external torque. This could better be described by the following equation:

$$\tau = \frac{dL}{dt} = \frac{d(Iw)}{dt} = I\alpha$$

where,

τ = torque

L = angular momentum

I = moment of inertia

w = angular velocity

α = angular acceleration

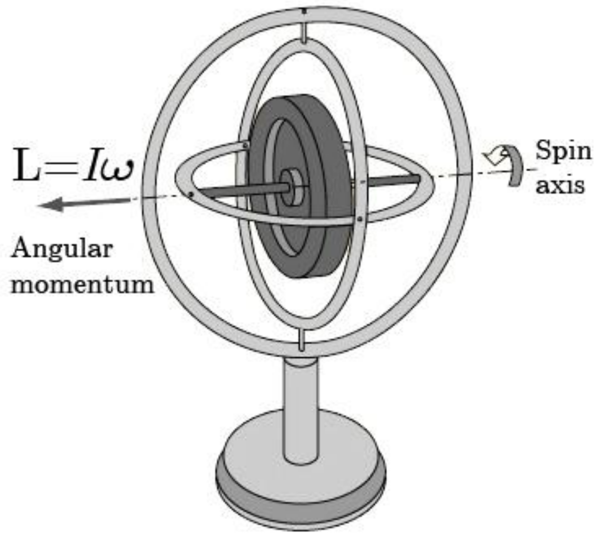

Figure 4.3 A conventional spinning wheel gyroscope (Gyroscope 2012).

Due to the revolution in the field of micromachined sensor technology the large sized and expensive gimballed and laser gyroscopes are being replaced by vibrating mass gyroscopes which are small, inexpensive and have low power requirements. They are more suitable and ideal for human motion analysis.

In the vibrating gyroscope vibrating resonator is subjected to a Coriolis force which causes Coriolis Effect that initiates a secondary vibration (Green and Krakauer, 2008). The resulting vibration is perpendicular to the original vibrating direction which provides the information about the rate of turn Figure 4.4.

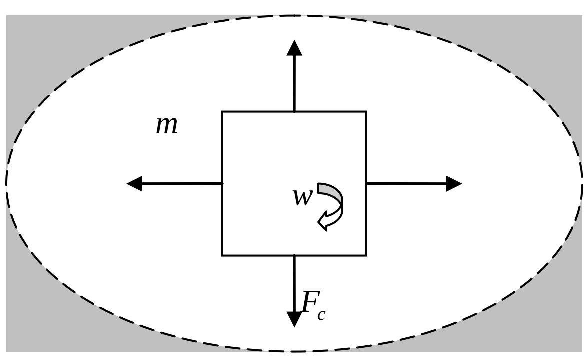

Figure 4.4A vibrating mass gyroscope

The governing equation of the Coriolis force (Haurwitz 1966) is given by:

$$F_c = -2m(w \times v)$$

where,

m = mass

v = speed

w = angular velocity

For similar purposes of detecting the resulting vibration some micro-electromechanical machined IMU's uses the piezo-electric effect. In our study the resulting vibrations has not been measured for any specific purposes.

In MEMS Gyroscopes the forces are proportional to the applied angular rate, from which the displacements can be measured in capacitive fashion. Electrostatic, electromagnetic, or piezo-electric mechanisms can be used to detect the force.

4.2.3 Magnetometers

These are the types of sensors used to measure the strength and/or the direction of the magnetic field in the vicinity of the instrument. Based on the principle of working, there are a number of different kinds of magnetometer such as flauxgate, proton precession, alkali vapour and magnetic gradiometers. Magnetometers are commonly used in industrial, oceanographic and biomedical fields. During the geomagnetic field measurement, magnetic pattern imaging, mineral deposit detection they serve as the pivotal sensor (Wickenden *et al.* 1998). In biomedical applications sensitivity and accuracy being the prime requirements magnetometers should also be small in size requiring low power. These qualities are not so satisfactory with the present day sensors.

MEMS technology provides an opportunity to solve this problem. Currently, the most popular principles in MEMS magnetometers are the Hall Effect, magneto-resistance and the fluxgate effect (Emmerich *et al.* 2000). However, Hall Effect magnetometers have low sensitivity and large temperature shifts; the sensors based on magnetoresistance are only appropriate to measure intense magnetic fields and fluxgate effect magnetometers are very difficult to fabricate

Hall Effect magneto resistive magnetometers are commonly used due to its small power consumption, easy sensing and its miniature size. The principle of Hall's effect sensor lies in the flow of electric current through the magnetic field thus causing a magnetic flux which exerts a force on the charges in motion. These charges then produce a potential difference across the magnetic field called the hall voltage. By measuring the amplitude of hall voltage the strength of magnetic field could be measured (Magnet. fsu 2008, Hubschmann and Schneider, 1996).

The Hall voltage could be mathematically by the following equation:

$$V_h = \frac{(\frac{-IB}{d})}{ne}$$

where,

V_h =Hall Voltage

I =bias current

n =charge density

e =charge on electron

In magneto resistive sensor magnetic fields causes a variable resistance which is later used in a wheat-stone bridge to measure magnetic field strength. Hall Effect method is very advantageous as it can directly sense the magnetic field strength.

Magnetometers in the Xsens sensors are used to measure the strength and direction of the local magnetic field which enables the north direction to be found. Since magnetometers output could be disturbed by the presence of any near by magnetic objects their data is fused with the gyroscope data to improve the accuracy of the calculated orientation.

4.2.4 Sensor Fusion

Estimation of position using micromachined gyroscope and accelerometers tend to produce lager errors resulting in inaccurate position estimation for periods longer than a second. The kinematics of the human movement can be obtained from the signals of 3D inertial measurement units which consist of accelerometers, gyroscopes and magnetometers. A proprietary algorithm called sensor fusion algorithms uses the data from these sensors which are then intermixed using a Kalman filter to obtain a drift free 3D orientation data for human movement analysis Figure 4.5 (Xsens, 2008). If an experiment is conducted in an environment where there is any possibility of some magnetic object a drift could occur over time. This also depends on the length of the experiment or the sensor working, for example in an experiment running over 10 minutes there could be a drift of 1° .

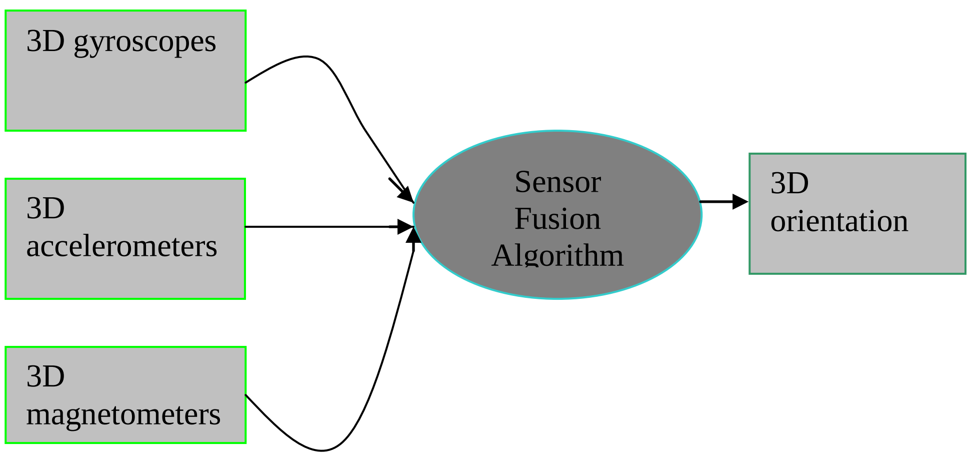

Figure 4.5Sensor Fusion Algorithm

The Kalman filter takes in to account a priori knowledge of gyroscope integration drift and presence of iron or other magnetic materials thus minimizing both drift and disturbances (Roetenberg *et al.* 2007a-b). This particular method of drift rectification is called attitude and heading referenced and such a system is termed as an Attitude and Heading Reference System (AHRS) (Xsens, 2008).

4.3 Sensors Performance and Error Analysis

Before using the sensors for the orientation estimation of the upper extremity during rehabilitation exercises using virtual platform, a reference system is essential in order to compare the experimental results. Thus the performance evaluation of the sensors is critical. It gives an idea of how to use these sensors accurately for certain applications. It also provides evident results on which further improvement and modifications could be performed. For the comparison of the results obtained from the sensors during trials on healthy individuals, robotic hand designs have been made. Experiments have been conducted and the results provide a reference for the trail results on healthy subjects. Sensor error and drift for the duration of rehabilitation task are based on the results obtained during the robotic experiments.

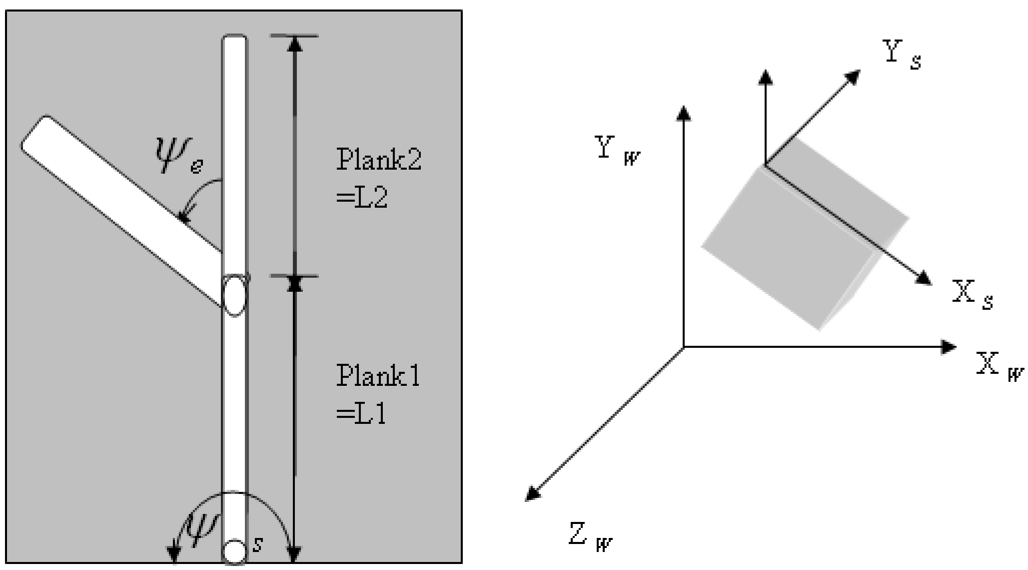

Figure 4.6 (a, b) 2D Plank Architecture

Figure 4.6(b) shows the architectural setup of the proposed 2D motion measurement system for performance evaluation. At first MT9 sensors are mounted on the two planks respectively which are able to move in the horizontal plane Figure 4-7. The sensors are aligned horizontally to the planks. The sensors reference frame and the world reference frame are shown in Figure 4.6(b). Three random points are chosen on the table and the end points of the two hierarchically attached planks are moved simultaneously performing five repetitions of each single point with different orientations of the planks. The physical implementation of the system is shown in Figure 4.7. The system has two degrees of freedom with constrained plank2 which is restricted to move from 0-90 degrees anti-clockwise and back, depicting as an elbow flexion and extension.

It was made sure the sensor does not move with respect to the planks once they are calibrated to the planks. Cables attaching the sensors to each other and the processing unit run between each of the components, minimizing interference in measurements by movements of the sensor and the possibility of restriction planks motion.

The sensor processing unit receives the rotation matrix, Quaternion and Euler Angles from each of inertial sensors and outputs the data to a PC via standard RS-232 interface. To avoid any interference in the output orientation data, the experiments were conducted where magnetic substances were absent in the radius of 2 meters from the centre of the experimental setup.

The overall aim of the experiment was to test the measurement repeatability and accuracy for the sensors in orientation estimation over a period of time and to find out any drift in measurements. These measurements and the errors observed in the measurements would serve as a comparison to the later rehabilitation exercises on healthy individuals and stroke simulated individuals. The trajectories for the experimental data have been plotted using Matlab and the Standard Error has been plotted using Microsoft Excel.

We assume the length of the planks (Plank1-L1, Plank2-L2) Figure 4.6 (a), also the Euler angles (φ, θ, ψ) are known from the MT9 sensors. These Euler angles are the XYZ (earth fixed type) i.e. they represent the orientation between the sensor reference frame that is S($X^S Y^S Z^S$) Figure 4.6(b) and the world reference frame i.e. W($X^W Y^W Z^W$).

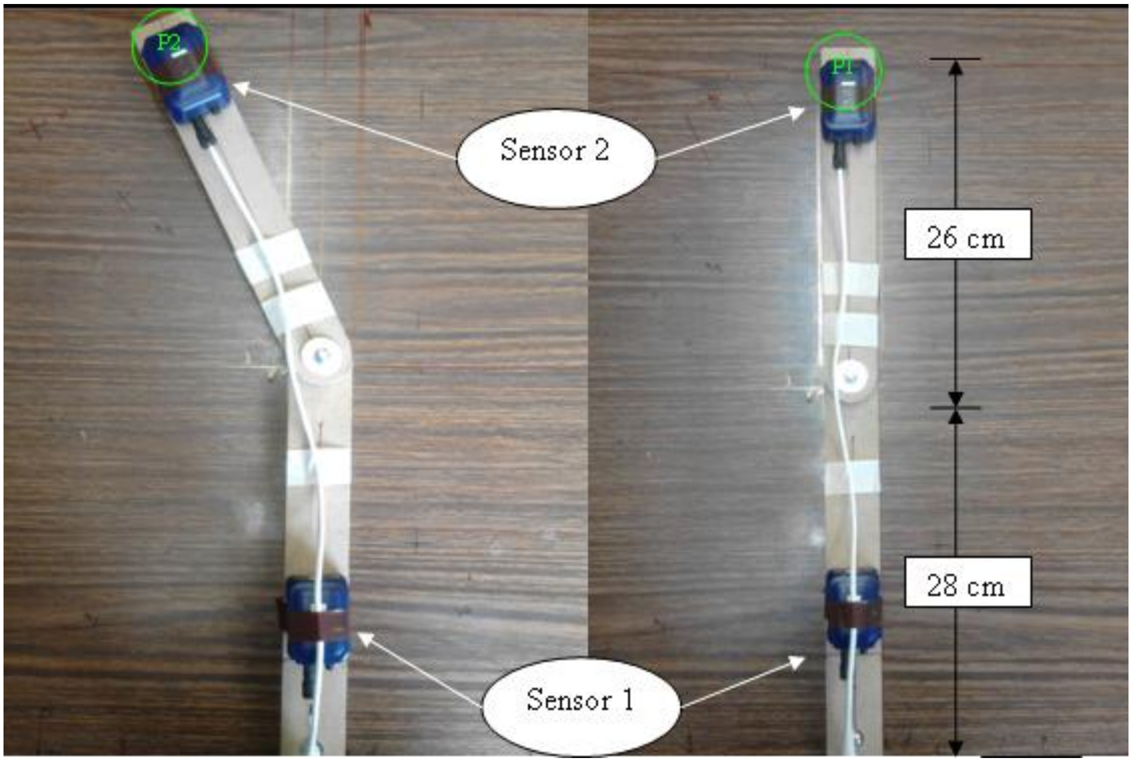

Figure 4.7Physical Implementation

From Figure 4- 8 the length of Plank1 and the Plank2 are L1 and L2 so the end point of Plank1 in sensor reference frame (S) is

$$P^{ES_1} = \{L1, 0, 0\}$$

Now, let the rotation matrix from the Plank1 coordinate system where the world reference frame (W) is fixed to the sensor reference frame (S) is R_W^S.

This is calculated from the Euler Angles (φ, θ, ψ) i.e.

$$R_W^{S_1} = R^{\psi,\theta,\varphi}$$

$$= R^{Z,\psi} \; R^{y,\theta} \; R^{x,\varphi}$$

Now the end point of Plank1 in the world reference frame is given by

$$P^E = R_W^{S_1} P^{ES_1}$$

With the similar approach we calculate the end point of the Plank2 in the world coordinate frame or for here the Plank1 coordinate frame as the world reference frame is coincident with the Plank1 coordinate frame.

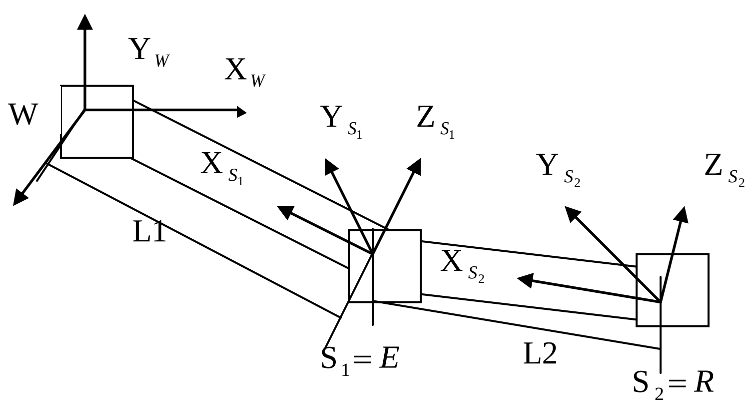

Figure 4.8Figure: End Position Estimation

Let, $R_{S_1}^{S_2}$ be the rotation matrix for Plank2 originating in Plank1 coordinate system.

Thus the end point of Plank2 is

$$P^R = R_{S_1}^{S_2} \; P^{RS_2} + P^E$$

Where, P^{RS_2} = {L2, 0, 0} assuming the X axis of the sensor reference frame is collinear with the X-axis of Plank2, also $R^{S_2}_{S_1} = R^{Z,\psi}\ R^{y,\theta}\ R^{x,\varphi}$

4.3.1 Experimental Results

The first random point was chosen at point P1(X, Y) where X is 28 and Y is -25 both in centimetres. Every time the planks are placed inline horizontal to the ground with the end point at the calibrated set position i.e. point (53, 0). The trajectories obtained during the five repetitions are given in Figure 4.9. While moving to P1, Plank1 observed anticlockwise rotation of 90 degrees while Plank2 was rotated to no rotation from the calibration position. Five repetitions were performed where the end point of the Plank1 is taken to point P1 and back to the starting position point (53, 0). The standard error in X position estimation is 0.0041 and the standard error in Y position estimation is 0.0011 Figure 4.10&11.

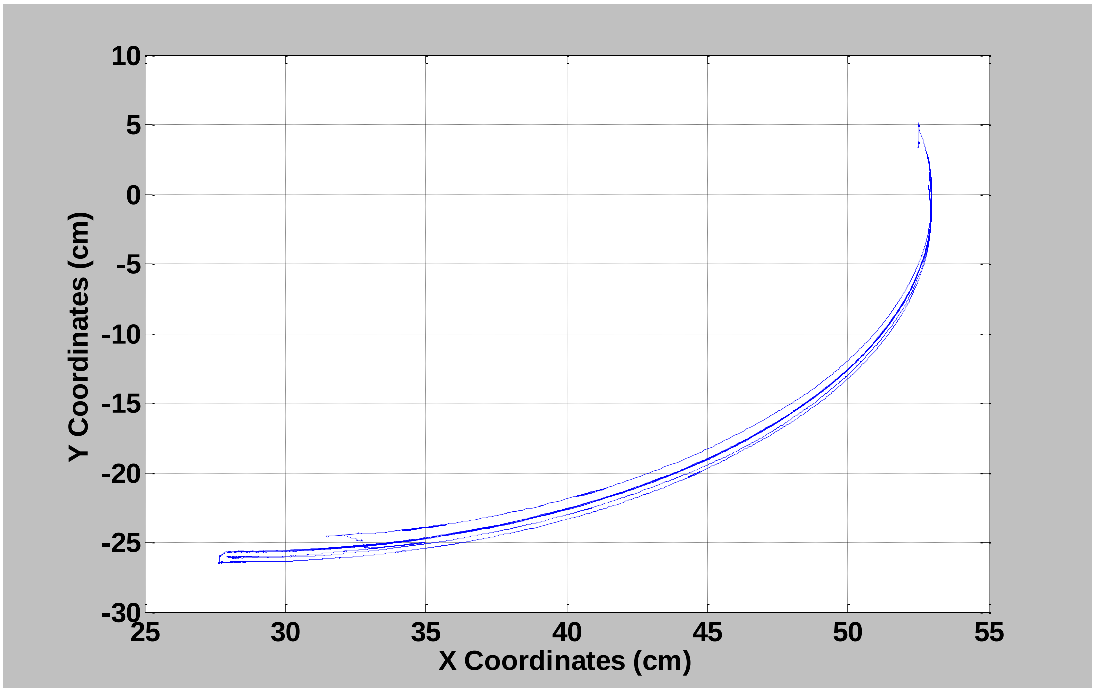

Figure 4.9Trajectory recovered during reaching point P1 (28, -25)

The mean of observed coordinates and the mean errors are plotted in Figure 4- 10 &11. Mean (WP_X) is the X-coordinates observed during five repetitions Figure 4-10 and Mean (WP_Y) is the Y-coordinates observed over five repetitions of the same point Figure 4-11.

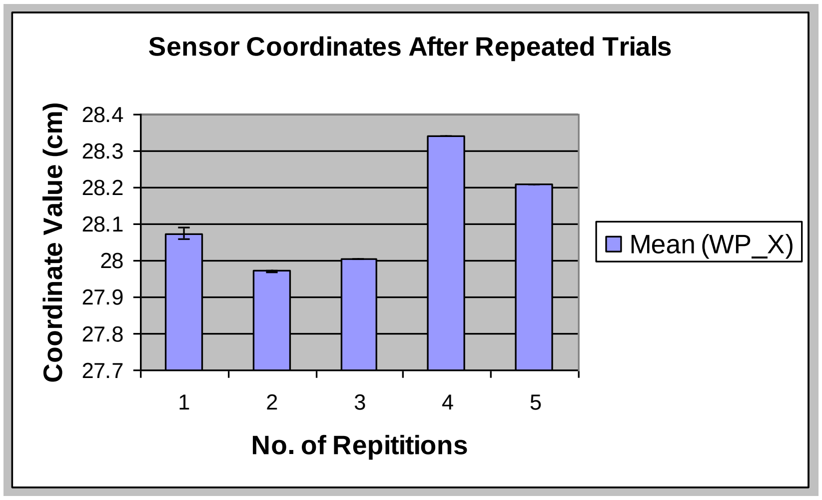

Figure 4.10 Error Plot for X-coordinates of Point P1 (28, -25)

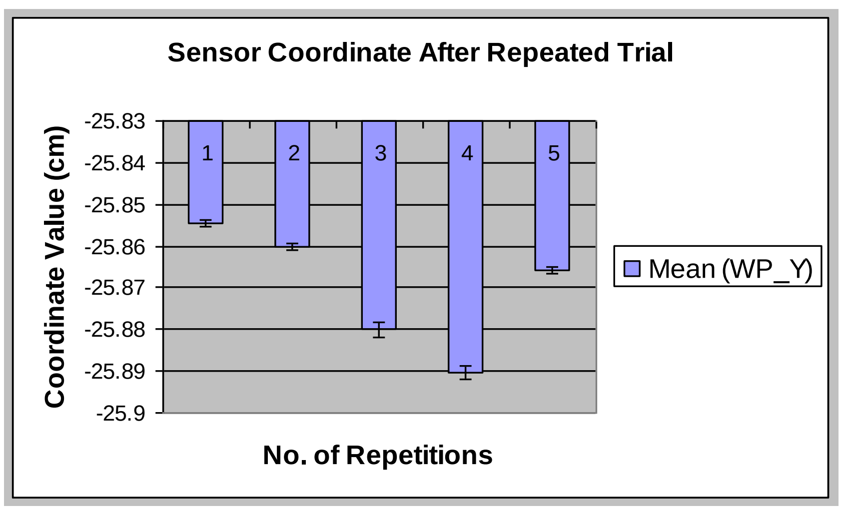

Figure 4.11 Plot for Y-coordinates of Point P1 (28, -25)

The second random point was chosen at P2 (45, -17) where X is 45 and Y is -17 both in centimetres. The trajectories obtained during the five repetitions are given in Figure 4-12. While moving to P2, Plank1 observed anticlockwise rotation of 45 degrees while Plank2 was rotated to no rotation from the calibration position. The standard error in X position estimation is 0.0120 and the standard error in Y position estimation is 0.0115 Figure 4-13&14.

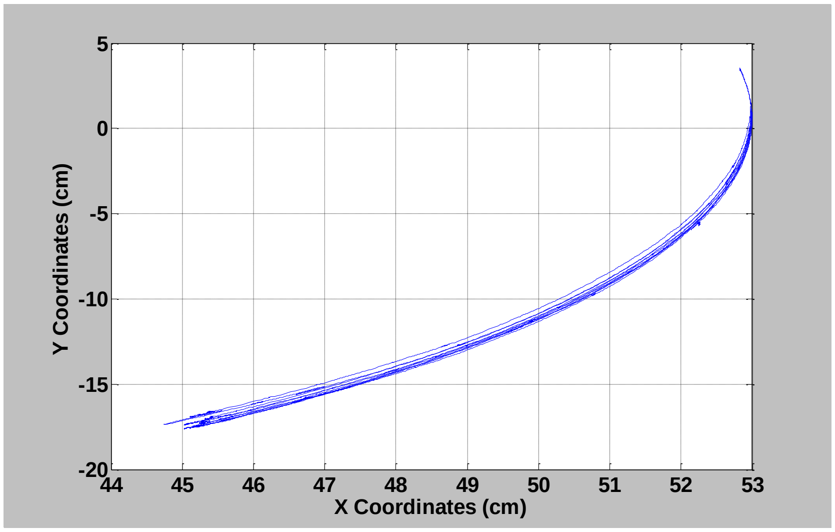

Figure 4.12 Trajectory recovered during reaching point P2 (45, -17)

The mean observed coordinates and the mean errors are plotted in Figure 4- 13 &14. Mean (WP_X) is the X-coordinates observed during five repetitions Figure 13 and Mean (WP_Y) is the Y-coordinates observed over five repetitions of the same point Figure 4.14.

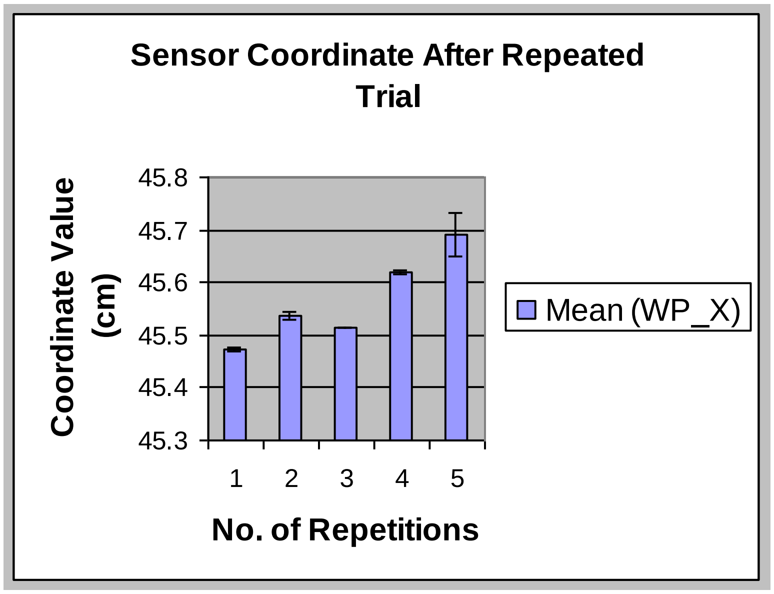

Figure 4.13 Error Plot for X-coordinates of Point P2 (45, -17)

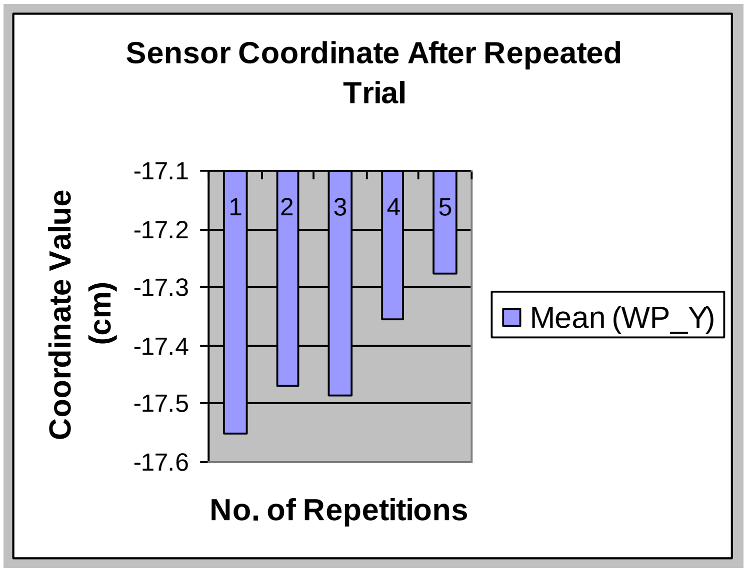

Figure 4.14 Error Plot for X-coordinates of Point P2 (45, -17)

The third random point was chosen at P2 (49, -13) where X is 49 and Y is -13 both in centimetres. The trajectories obtained during the five repetitions are given in Figure 4-15. While moving to P3, Plank1 observed anticlockwise rotation of 30 degrees while Plank2 was rotated to no rotation from the calibration position. The standard error in X position estimation is 8.3458e-004 and the standard error in Y position estimation is 0.0019 Figure 4.16&17.

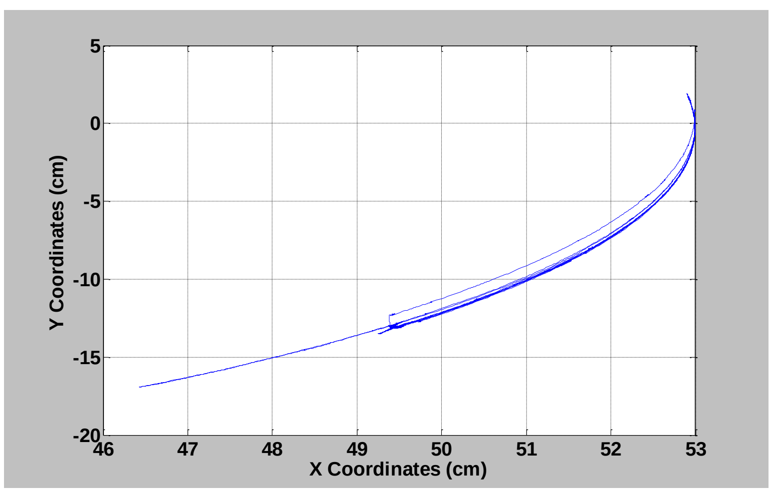

Figure 4.15Trajectory recovered during reaching point P3 (49, -17)

The mean observed coordinates and the mean errors are plotted in Figure 4-16 &17. Mean (WP_X) is the X-coordinates observed during five repetitions Figure 4-16 and

Mean (WP_Y) is the Y-coordinates observed over five repetitions of the same point Figure 4-17.

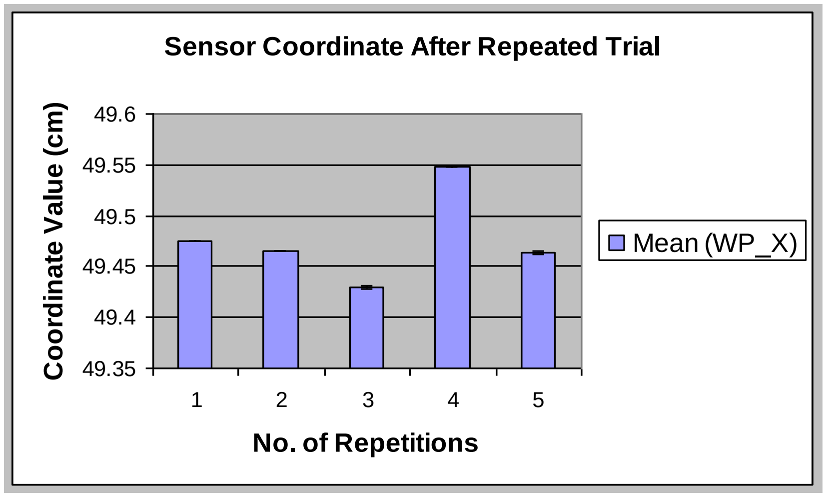

Figure 4.16Error Plot for X-coordinates of Point P3 (49, -13)

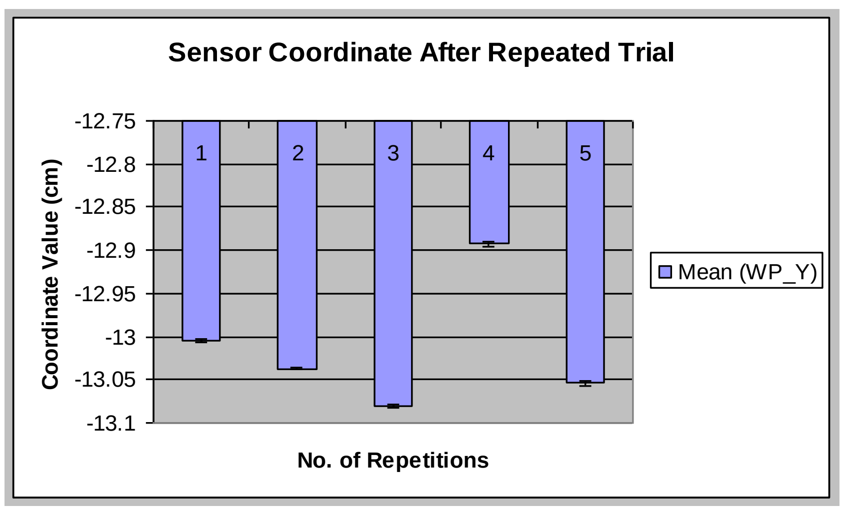

Figure 4.17Error Plot for Y-coordinates of Point P3 (49, -13)

The fourth random point was chosen at P2 (44, 22) where X is 44 and Y is 22 both in centimetres. The trajectories obtained during the five repetitions are given in Figure 4-18. While moving to P4 Plank1 observed zero rotation while Plank2 was rotated to -45 degrees clockwise from calibrate position. The standard error in X position estimation is 0.0011 and the standard error in Y position estimation is 0.0012 Figure 4-19&20.

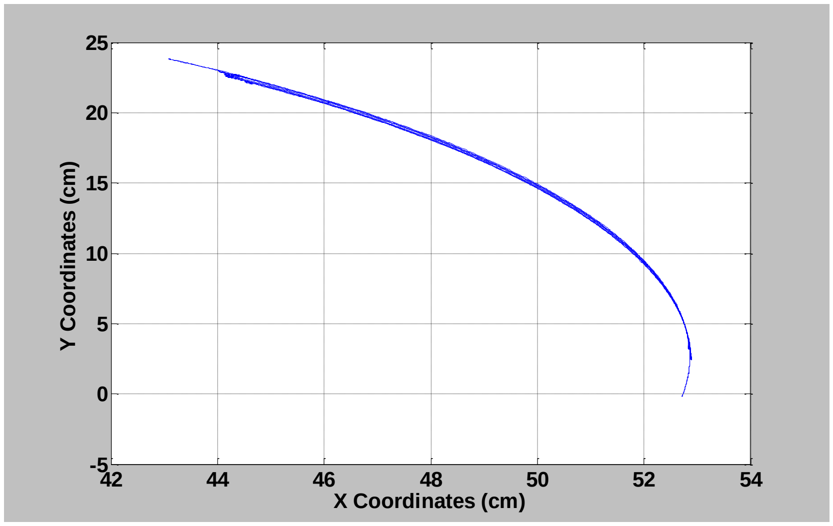

Figure 4.18Trajectory recovered during reaching point P4 (44, 22)

The mean observed coordinates and the mean errors are plotted in Figure 4-19 &20. Mean (WP_X) is the X-coordinates observed during five repetitions Figure 4-19 and Mean (WP_Y) is the Y-coordinates observed over five repetitions of the same point Figure4- 20.

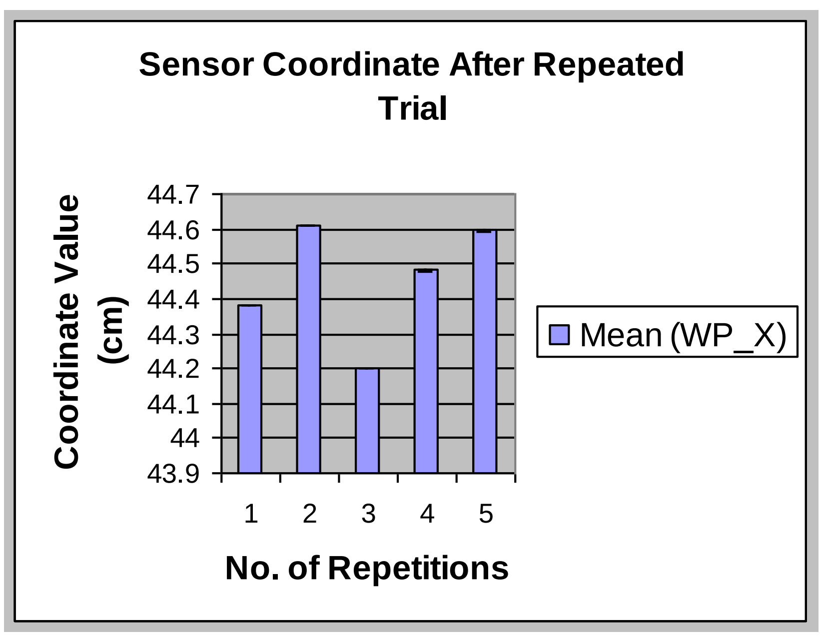

Figure 4.19Plot for Y-coordinates of Point P4 (44, 22)

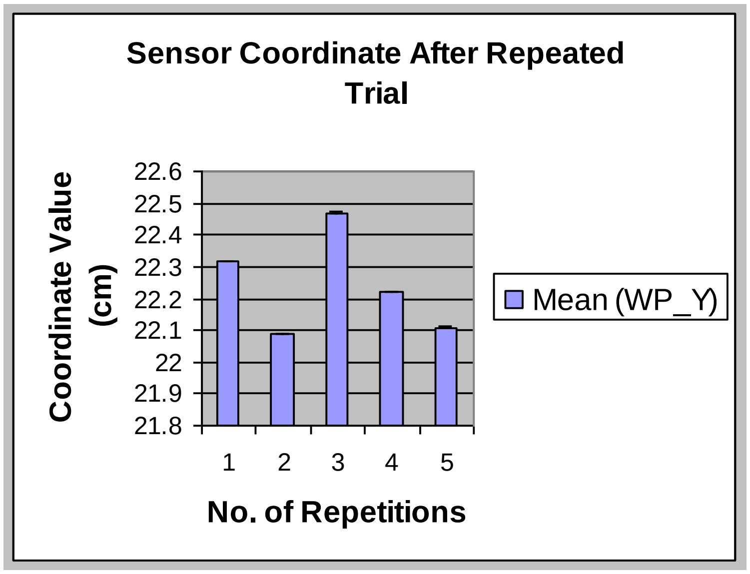

Figure 4.20Plot for Y-coordinates of Point P4 (44, 22)

The fifth random point was chosen at P2 (24, 29) where X is 24 and Y is 29 both in centimetres. The trajectories obtained during the five repetitions are given in Figure 4-21. While moving to P5 Plank1 observed zero rotation while Plank2 was rotated to -90 degrees clockwise from calibrated position. The standard error in X position estimation is 0.0018 and the standard error in Y position estimation is 0.0011 Figure 4-22&23.

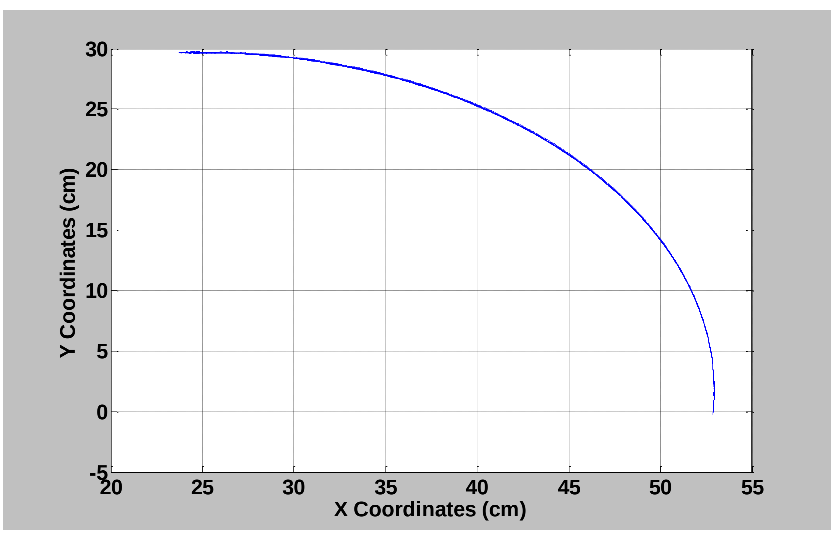

Figure 4.21Trajectory recovered during reaching point P5 (24, 29)

The mean observed coordinates and the mean errors are plotted in Figure 4-22 &23. Mean (WP_X) is the X-coordinates observed during five repetitions Figure 4-22 and Mean (WP_Y) is the Y-coordinates observed over five repetitions of the same point Figure 4-23.

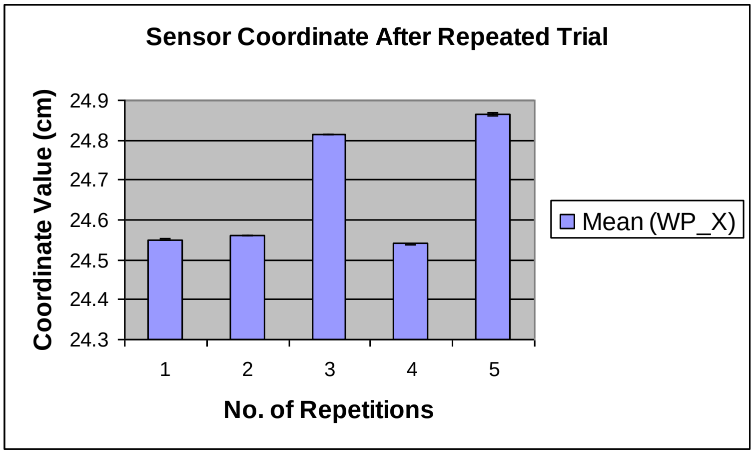

Figure 4.22Plot for X-coordinates of Point P5 (24, 29)

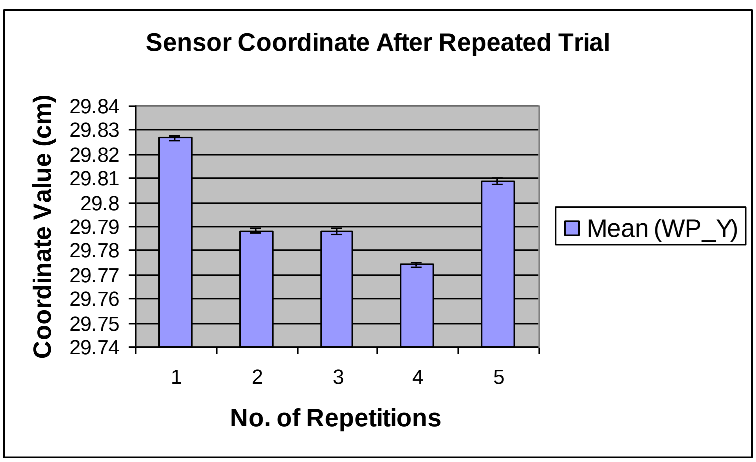

Figure 4.23Plot for Y-coordinates of Point P5 (24, 29)

4.4 Conclusion

The selection of inertial measurement system have been made and justified. Given the sensor signals the inertial measurement unit provides orientations in 6 DOF. Experiments were performed on a self made 2 DOF planar arm. The experimental results show the feasibility of the proposed measurement system as a reference to the later stage of trials on healthy individuals and stroke simulated subjects. A full evaluation would be performed during the rehabilitation tasks performed during the full and constrained range of motions of the upper extremity while performing the virtual tasks. Experiments were conducted on a relatively slow pace to avoid any errors due to the relative movement between the sensor and the source within one cycle. The relative position and orientation are assumed to be fixed in the algorithm for calculation of end position of 2 DOF robotic hand. The MT9 sensors were tested in the absence of conductive or metallic materials within a range of two meters to decimate their effects on the accuracy of orientation estimates.

After the repeatability and accuracy testing of the motion sensors, the design of the virtual environment is targeted. The virtual environment would consist of the virtual arm and hand and virtual objects in the virtual room used for feasibility testing. This would require looking at some of the building blocks of 3D programming used in the design strategy.

CHAPTER 5. Virtual Environment Design

One of the major components of virtual reality based stroke rehabilitation system is the virtual environment consisting of the virtual upper extremity and the virtual scene depicting the real world space or place such as a room or a kitchen. In this chapter the design and development of such a virtual environment for upper extremity stroke rehabilitation will be presented. Upper extremity is a human limb which is connected by links and joints defined in a hierarchical manner which forms a kinematic chain. Furthermore, a kinematic model of the human upper extremity, hand and fingers has been presented. For the design of the upper extremity in 3D, the selection of a programming language has been made in order to develop a three dimensional representation of the shoulder, upper arm, fore arm, hand and fingers. After the selection of the programming language a step by step methodology and implementation has been presented to design the final prototype. After the design of the virtual environment a hardware software interface has been established to access the inputs from the motion sensors described in Chapter 4. The 3D orientation from the motion sensors are used to manipulate the virtual scene in real time. This was done to finally analyze upper extremity motion during the execution of activities of the virtual task in the computer simulated virtual environment.

Human motion is driven by numerous principles and showcases wide range of appearances (Simonidis *et al.* 2009, Legget 1997, Schleihauf 2004). From simple to complex, human motion thrives on the basic need of action sequence involved during the execution of ADL's. Fields ranging from keinsology (the study of human anatomy and the mechanics of body motion) to computer vision require a thorough knowledge of human motion. The fields of orthopedics, biomechanics, rehabilitative procedures, athletics analysis and sports medicine also use human motion analysis. Human motion analysis also facilitates a higher degree of accuracy and in-depth understanding of the human body which initiates a better performance in other fields such as choreography, gymnastics, figure skating, ethnic folklore studies and behavioral studies. The techniques of human motion analysis in these aforementioned scenarios require capture, measurement, analysis, representation and classification of human motion.

5.2 Analysis of Human Motion

To analyze human motion the immediate requirement lies in breaking down the complex biological model of the human upper extremity in to simpler accessible units. In computer graphics a human model could be represented by simple links and joints (Badler *et al.* 1999). These links are connected by joints to form a complete limb. This complete limb is termed as skeletal model of the primitive biological system ready to be modeled which would later depict similar motion patterns as seen by the human limb. So, the skeletal structure of the upper extremity could be represented by a tree graph where the joints are the nodes of the tree and the bones are the representative arcs. In the upper extremity tree model the base or the root of the hierarchy is the trunk. The three dimensional pose of bone could be represented by its position and orientation. Each recursive movement leads to a transformation which could well be broken down into a translation and a rotation. In a hierarchical structure each translation is dependent on the translation of the preceding bone in the tree structure because of the close connections of the bones by the flexible joints. During the modeling of the upper extremity the only independent translation is the translation of the trunk which has been described as the root translation Figure 5.1. For our design the posture and motion of the upper extremity has been determined by the three dimensional angular orientation (rotation around the 3 axes, xyz, also known as Euler angles) “fed” in real time from the motion sensors worn by the subject during training with the virtual environment.

5.3 Hierarchical structure of Upper Extremity

Human upper extremity is a complex structure consisting of bones, joints, muscles and other elements. In order to examine the motion pattern laid down during its iterative movements performed when executing a functional task, a skeletal structure could well represent its simplified organization. The tree structure of the upper extremity model Figure 5.1 illustrated in the design has been presented in Figure 5.2.

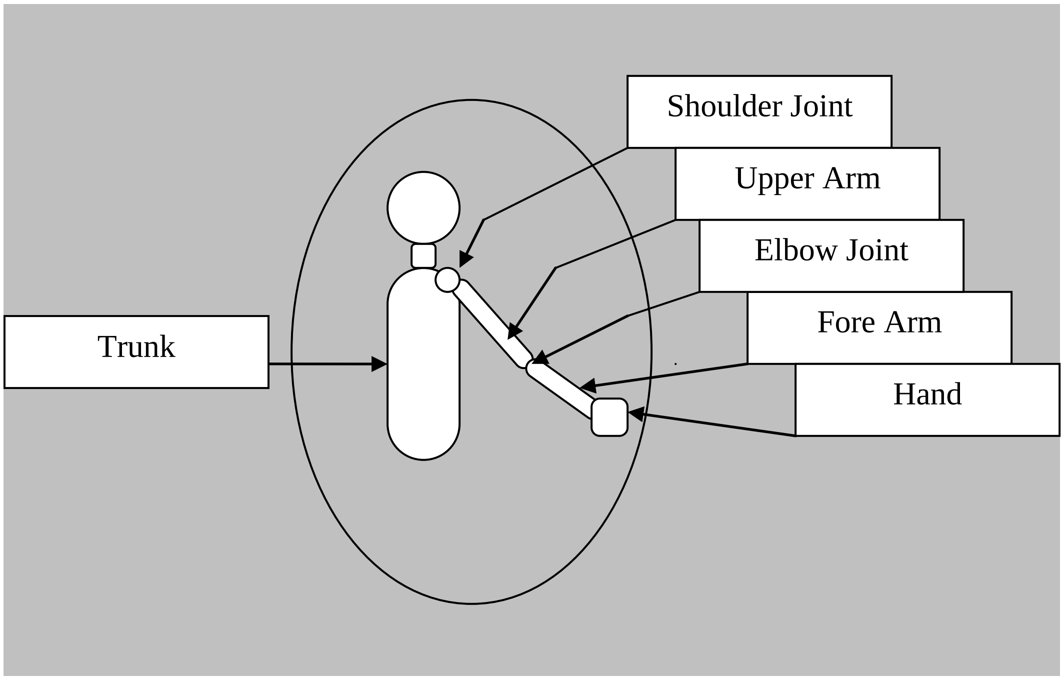

Figure 5.1 Representation of Human Upper Extremity

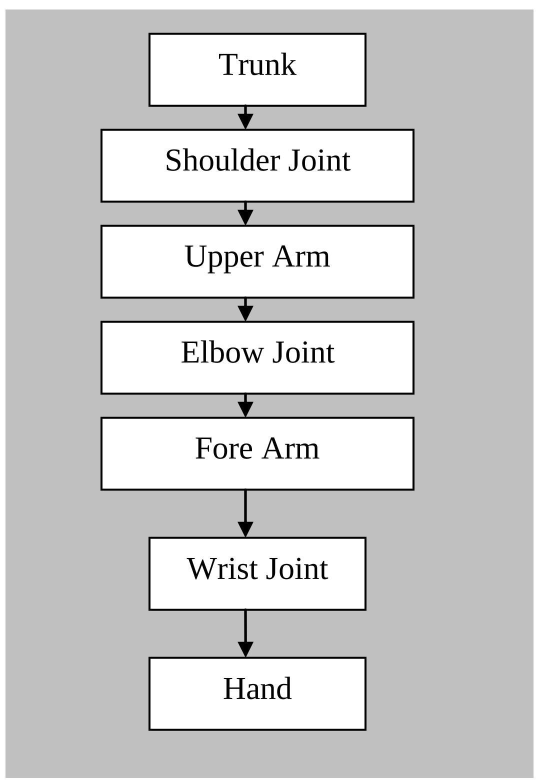

Figure 5.2 Hierarchical structure of Upper Extremity

It could be observed from Figure 5.1 and Figure 5.2 that the trunk occupies the top of the upper extremity hierarchy; the shoulder consists of the upper arm, the fore arm, the wrist, the hand. The hand consists of the palm, fingers and the thumb. The forearm connects the shoulder (upper arm) and the hand.

A tree structure is often used to design algorithms for the movements of the objects that are connected in some order where the movements of a parent node will automatically propagate to all of its child nodes (children). The final movements observed by the child are the cumulated combination (matrix multiplication) of the movements of all its parents in the tree. For example, forearm's movement not only includes its own motions (bending and twisting) but also depends on the movement of shoulder and that of trunk.

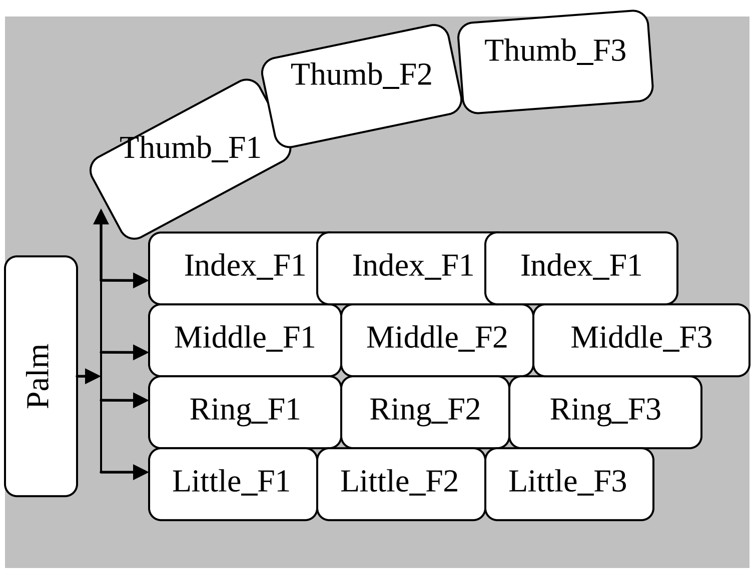

Figure 5.3 Hierarchical structure of the Hand and Fingers

In our upper extremity design the hand is divided into a palm, four fingers and a thumb; a finger is further split into three finger parts; and all the hand parts are connected in a more complicated tree structure Figure 5.3. With the placement of a local coordinate system at every joint the nodes transformation could be simplified. This way the transformation of the corresponding joints are related and the final movements could be interpreted logically with realism. In the upper extremity tree structure a local coordinate system is attached to every node and the movement of each part in its local coordinate system gets transformed into the tree structure of their corresponding coordinate systems, as illustrated in Figure 5.4.

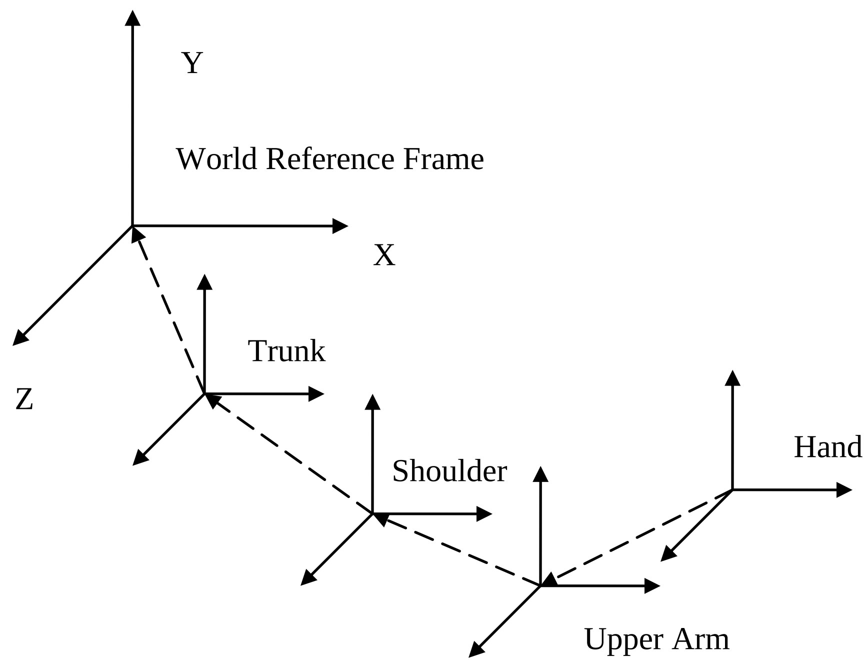

Figure 5.4Coordination of motion of Upper Extremity

The overall upper extremity skeletal structure could be exemplified as a rigid body system. When a rigid body undergoes a pose change it follows the laws of homogeneous coordinate transformation (Jazar 2007). Irrespective of the direction of motion, each transformation consists of a rotation and translation which forms a 4×4 transformation matrix T_M . A sequence of matrix multiplication leads to the desired motion patterns.

$$T_M = \begin{bmatrix} r_{11} & r_{12} & r_{13} & x \\ r_{21} & r_{22} & r_{23} & y \\ r_{31} & r_{32} & r_{33} & z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Using the above description, the movement of the forearm at its local coordinate system can be described with a 4×4 matrix R_{FL}, whereas a relationship between the transformation matrices of forearm and shoulder in the local coordinate system could be given by R_{FS}. Similarly, the relationship between the shoulder and the trunk could be given by R_{ST} as well as the relationship between the trunk and the world coordinate system could be given by R_{TW}. Hence the movement of the forearm in the world coordinate could be represented by the final transformation matrix obtained by the following multiplication sequence;

$$R_{FW} = R_{TW} \times R_{ST} \times R_{FS} \times R_{FL}$$

These relationships amongst the coordinate systems provide a clear 3D design strategy and hence nullify any undesired motion patterns which may arise from any misalignment of nodes. This also makes the programming of the virtual environment in the OpenGL API easier.

5.3 Modelling Approaches

The use of the hierarchical structure of the upper extremity different kinematics and dynamics methods could be applied to model the human upper extremity (Admiraal et. al 2004). Dynamics methods tend to bring more naturalness in processing the movements of the upper extremity. Though very effective, both kinematics and dynamic models fail to incorporate all the rigid and non-rigid variables involved in human motion. Planning of the models based on the anatomy of the upper extremity is suggested to have a better outcome in terms of realistic behavioral modeling (Porcher-Nedel *et al.* 1998, Scheepers *et al.* 1997)

Taking into account the anatomy of the human body, there are different approaches to modeling human body in computer graphics such as stick figure models, volume models, surface models and multi-layered models Figure 5.5 (Gudukbay *et al.* 2008). Stick figure modeling incorporates the basic idea of rigid bodies which are composed of links and joints. Some of the early research work in the area used stick figure models very effectively (Badler & Smoliar 1979). Though effective however the overpopulation of the links and joints in the stick figure models could cause complexity issues. Geometric primitives such as spheres, ellipsoids have been used at times to explore the idea of complexity in the articulated modeling. To proficiently answer the weaknesses in the stick figure model surface models were introduced. Links and joints were covered by a surface, thus making it a two-layered modeling approach (Badler 1992).

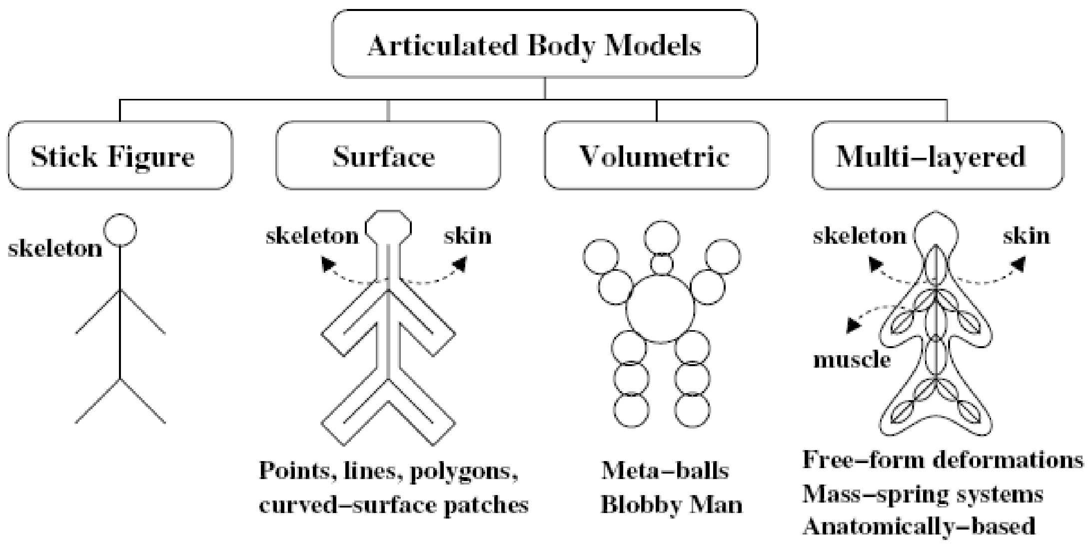

Figure 5.5 Taxonomy of Articulated Body Model (Gudukby *et al.* 2008)

The second layer or the surface deformation caused the model to be unstable during the model transformation. Volume models took into account the surface deformation as they use volumetric primitives such as ellipsoids, spheres and cylinders.

When the number of primitives increases in the body shape it becomes tedious to control the transformation. To make the models more realistic a three-layered approach came into being where the model of the human body consists of a skeleton layer, intermediate layers (muscles, fat, bones) and the skin layer to simulate the body animation consistent with human physical aspects (Lasseter 1987). Though complex, it makes the visualization of the human body more realistic and accurate.

Since the deformation is not taken into account for the modeling of the upper extremity, only stick figure models along with volume models are considered for our design (Figure5. 6).

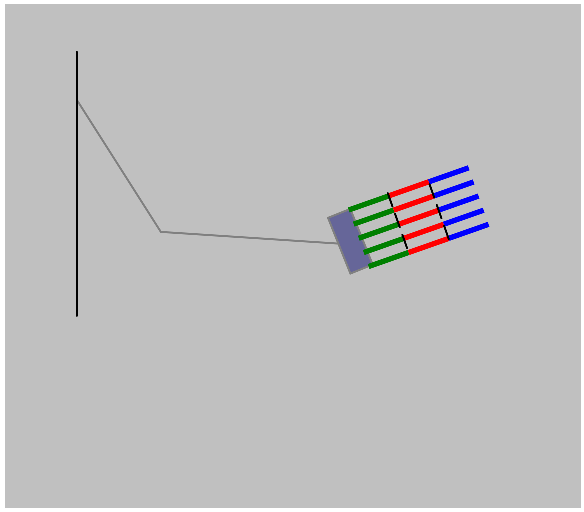

Figure 5.6 Stick and Volume Modeling of Upper Extremity

Modeling of the upper extremity has been motivated by the real time audio/visual feedback mechanism and the compatibility and feasibility of the hardware software interface.

5.4 Modeling Virtual Environment-OpenGL

To model the upper extremity as a virtual avatar which imitates the real time trajectory moved by the subject, industry standard OpenGL programming language was used. It is an open-source API library which is free and very extensively used in the industry. It is also, according to many, one of the most fully supported and best documented 2D/3D graphics APIs. Additionally, it is widely compatible with other programming languages such as C and C++. Finally, it is independent of Windows systems and any other operating systems producing uniform visual display. One of the disadvantages of the basic OpenGL library was that it was unable to open Windows or react to interferences from a mouse or keyboard (Whitrow 2008). This problem was tackled with the advent of

GLUT (OpenGL Utility Toolkit) library by Mark Kilgard (www.opengl.org) and freeglut, which came with an open-source license and thus provided solutions to such shortcomings.

Most of the applications of OpenGL have a similar order of operations, a series of processing stages called the OpenGL rendering pipeline (Shreiner *et al.* 2003). The order of operation according to Henry Ford assembly line approach for processing data is shown in Figure 5.7 (Shreiner *et al.* 2003).

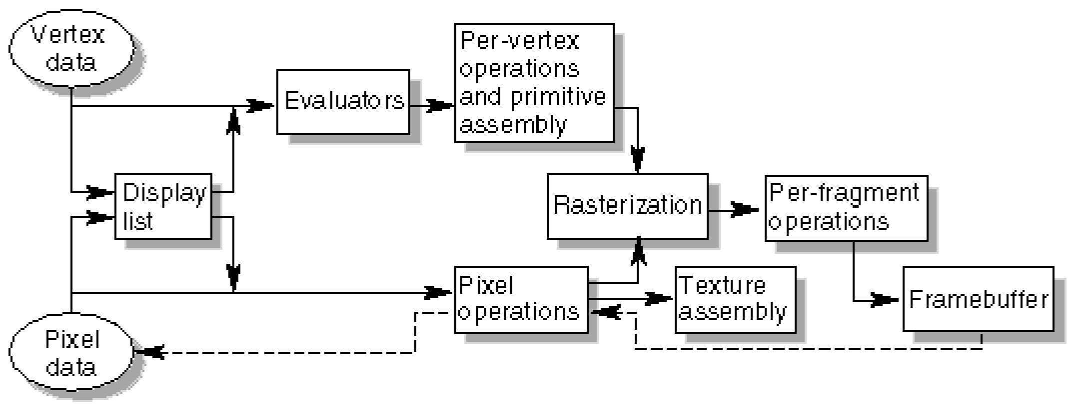

Figure 5.7 Order of Operations in OpenGL (Shreiner *et al.* 2003)

As it can be seen from the Figure 5.7; the vertices, lines and polygons go through evaluations and pre-vertex operation in the mean time the pixel data from the textures of the objects and the objects itself follows a different process. These two processes represent two types of processes but at the end of the operations they undergo rasterization and pre-fragment operations. The final process where the framebuffer takes the charge to conclude the object being drawn on the OpenGL screen comes at last. The same rendering pipeline has been followed to draw the upper extremity and the virtual environment proposed in the thesis Figure 5.8

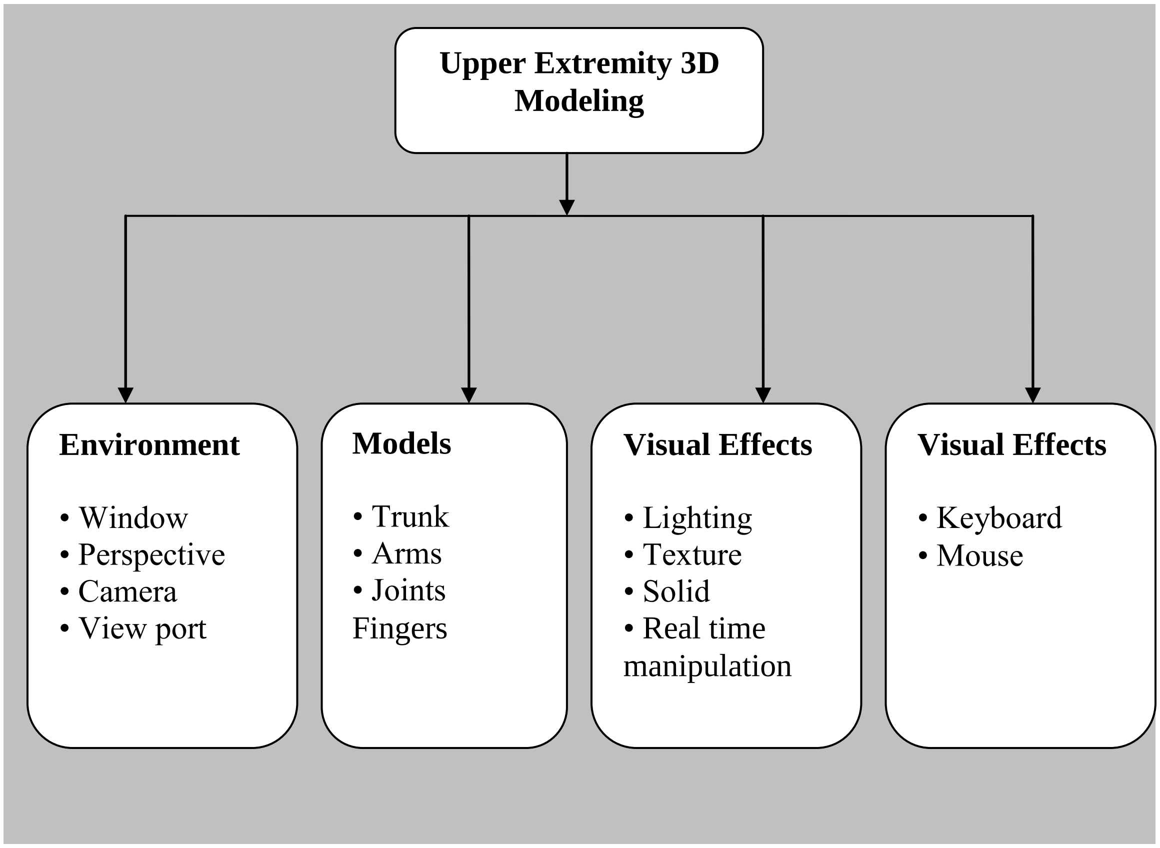

Figure 5.8Upper Extremity Model Rendering Structure

5.4.1 Basic Initialization OpenGL

The first step before the actual drawing of objects in OpenGL is to set up a basic OpenGL window. Thereafter the objects can be assigned a colour, texture and could be tested for any collision with any other objects in the scene. The basic OpenGL window is set up through the initialization of GLUT (an OpenGL Utility Kit) that also specifies the window size and position (Shreiner *et al.* 2003, Hill & Kelly 2007). After the GLUT initialization, buffers are allocated to store vertex data or pixel data retrieved from the drawn objects. The choice of a buffer varies depending on the attributes such as depth testing etc. There are options for a single or double buffered window but in our design we have used GLUT_DOUBLE which gives a double buffered window with depth testing enabled. Figure 5.9 shows the basic code used for the initialization of display window done for GLUT, before the drawing and transformations of the OpenGL objects.

```
glutInit(&argc, argv); // initialise GLUT toolkit
glutInitDisplayMode(GLUT_DOUBLE|GLUT_DEPTH|GLUT_RGBA | GLUT_STENCIL);
// initialise display mode
glutInitWindowSize(w, h); // initialise window size
glutInitWindowPosition(x,y); // initialise window position
glutCreateWindow("Title:VR based UE Rehab. SYS."); // open the window
glutDisplayFunc(UL_display); // register display callback function
glutReshapeFunc(UL_reshape); // set the reshape callback for the current window
glutMainLoop(); // enter GLUT event processing loop
```

Figure 5.9 Initialize a GLUT window

Once GLUT is initialized, reshape () function is called which handles the functionality of the window alterations; in case of a window creation or overlay (Shreiner *et al*. 2003, Hill & Kelly 2007). Consequently the correct viewport, viewing perspective and camera variables are set under the reshape callback in order to make the scene mirror a relative projection of the real world objects i.e. the upper extremity in this case (Figure 5.10).

```
glMatrixMode(GL_PROJECTION); // set the coordinate system to projection matrix
//stack
glLoadIdentity();
glViewport(0, 0, w, h); // Set the viewport with width and height, h
gluPerspective(angle, w / h, near, far); // Set the correct perspective
gluLookAt(x,y,z,0,0,0,0,1,0); //eye position (x,y,z), look at point (x,y,z), up direction
//(x,y,z)
glMatrixMode(GL_MODELVIEW); // reset the coordinate system to modelview matrix
//stack
glLoadIdentity();
```

Figure 5.10 Setting for Viewing Volume

Each time the window is resized gluPerspective () is called which specifies a symmetrical projection and a viewing volume into the world coordinate system. To obtain a realistic scenario the aspect ratio in the gluPerspective() should match the aspect ratio of the associated viewport. In the gluPerespective () the view angle is in the y-direction with the specification of a distance of the viewer from the near and far clipping plane (Shreiner et. al 2003, Hill & Kelly 2007).

5.4.2 Drawing the Upper Extremity

After the environment setting and the perspective correction the upper extremity needs to be modeled. The choice of the primitive is inspired from the earlier discussion about the approaches of 3D modeling.

```
drawUEObject(){ // objects in the virtual environment
glPushMatrix(); // push the current matrix stack
glColor4f(r,g,b,a); // set the current colour
glTranslatef(x,y,z); // translate current object
glRotatef(angle,x,y,z); // rotate current object
glScalef(x,y,z); //scale current object
gluCylinder(quad,base,top, height,slices,stacks) //draw a sphere
glPopMatrix(); // pop the current matrix stack
} // drawUEObject
```

Figure 5.11Object construction sub-routine

To present a close resemblance of the 3D model with the human upper extremity cylinder quadrics have been used to model the upper arm, fore arm and the fingers (Figure 5.13). The GLUquadrics objects are available from the OpenGL Utility Library to draw cylinders, spheres and disks. The palm is modeled using a scaled cube which is a basic shape available in GLUT with glutSolidCube() and glutWireCube()(Shreiner et. al 2003, Hill & Kelly 2007). The joints in the upper limb are modeled using a sphere which is drawn with gluSphere(). The basic object construction sub-routine for each part is shown in Figure 5.11 & Figure 5.12.

```
void UECylinderObj(GLUquadricObj* object, GLdouble topRadius, GLdouble
baseRadius, GLdouble lenght, GLint slices, GLint stacks)
{
    glPushMatrix();
    gluCylinder(object, baseRadius, topRadius, lenght, slices, stacks);
    glTranslatef(0.0, 0.0, lenght);
    gluDisk(object, 0.0, topRadius, slices, stacks); // top cover
    glRotatef(180, 0.0, 1.0, 0.0);  // flip
    glTranslatef(0.0, 0.0, lenght);
    gluDisk(object, 0.0, baseRadius, slices, stacks); // base cover
glPopMatrix();
```

Figure 5.12 Method in order to draw a cylinder

The Upper Extremity is drawn using the above conditions and utilizing the objects hierarchy with the use of volumetric primitives..

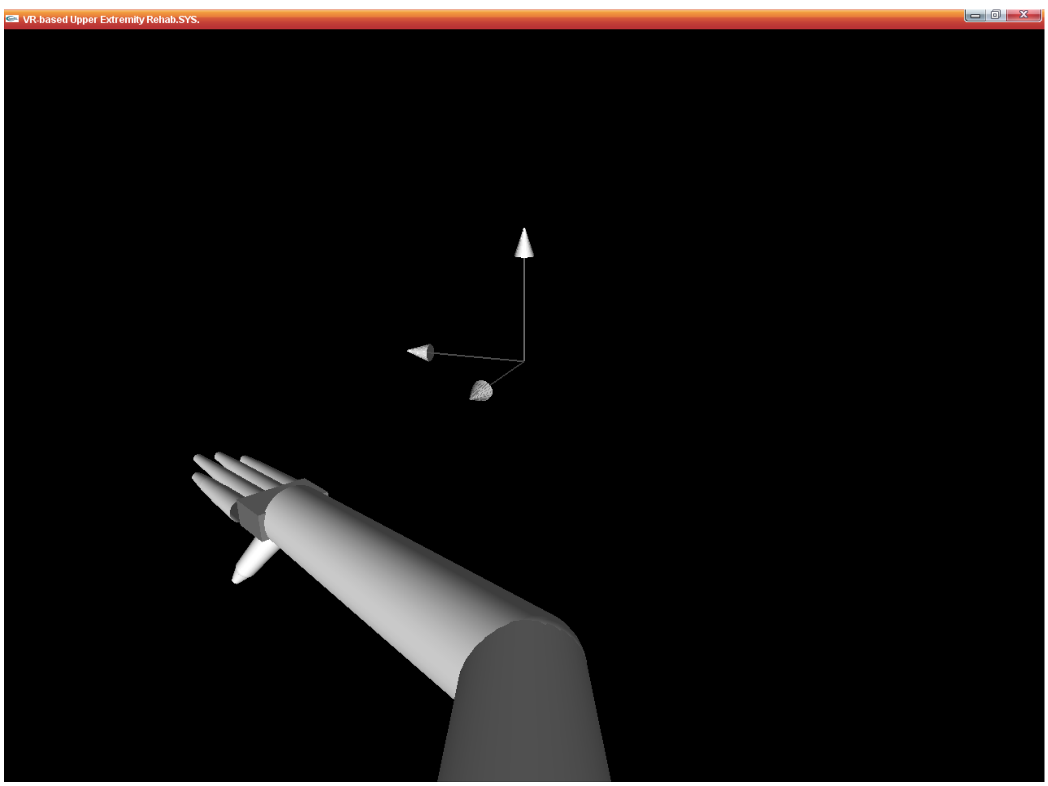

Figure 5.13 Upper Extremity Model without Color and Texture(s)

The upper extremity is drawn on the positive Z-axis while the viewing direction is from the negative Z-axis towards the far clipping plane lying on the positive Z-axis (Figure 5.13)

5.4.3 Realistic Visualization

To make the scene bright in order to correctly identify the objects in the scence different visual effects have been used. The upper extremity is modelled as a solid structure which is smoothed with more slices along the radius and height (Figure 5.14 and Figure 5.15). A virtual room and a table are drawn in the scene. Objects are drawn on the table falling under and in the workspace of the virtual upper extremity which would resemble actual human movements performed during the rehabilitation exercises. These additions of the virtual objects and the walls provide an interactive and immersive experience to the user which would provide motivation for a longer training session (Figure 5.16).

```
glEnable(GL_LIGHTING); // enable lighting effect
glEnable(GL_DEPTH_TEST); // enables depth calculations with depth buffer for
//hidden surfaceremoval
glShadeModel(GL_SMOOTH); // smooth surface
gluQuadricNormals(obj, GLU_SMOOTH); //smooth normal for quadric object
gluQuadricDrawStyle(obj, GLU_FILL); // solid object draw style
```

Figure 5.14 Visual effects

```
glDisable(GL_LIGHTING); // disable lighting effect
glDisable(GL_DEPTH_TEST); // disable depth calculations with depth buffer for
hidden surface removal
glShadeModel(GL_FLAT); // flat surface
gluQuadricNormals(obj, GLU_NONE); // no normal
gluQuadricDrawStyle(obj, GLU_LINE); // wire frame draw style
```

Figure 5.15 Visual effects

To simulate the overall scene like the actual physical object in the real world environment textures need to be applied. There are different methods to apply texture to the scene. One of the examples shown in Figure 5.17 outlines different texture and texture mapping which could be used in the program (Shreiner *et al.* 2003). The textured scene is shown in Figure 5.19.

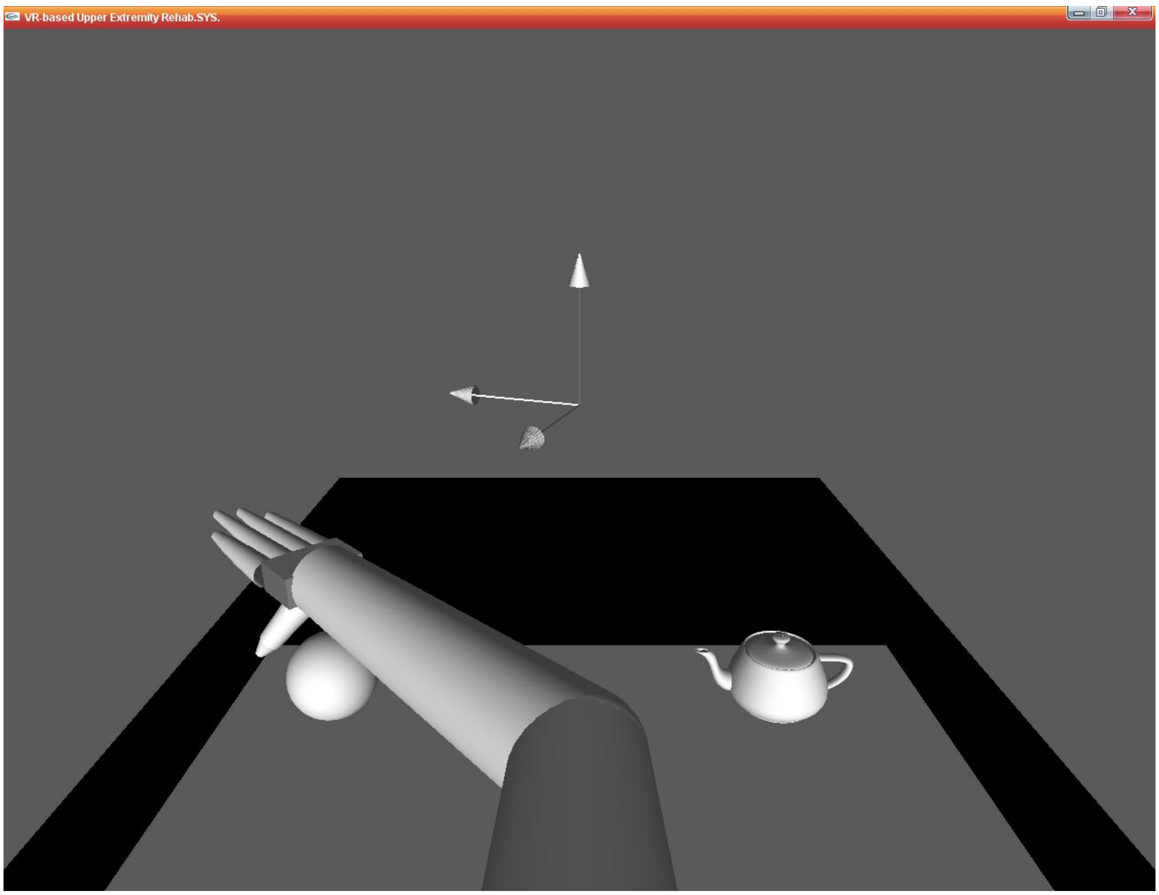

Figure 5.16 Upper Extremity with a basic Interactive Virtual Environment

The shadow of the upper extremity and the objects are essential for depth testing and for the sense of realism. Stencil test is carried out in order to model the shadow where stencil GLUT_STENCIL is added to the glutInitDisplay() function (Figure 5.9).

```
// define storage for texture map
GLubyte image[IMAGE_WIDTH][IMAGE_HEIGHT][3];
for (i = 0; i < IMAGE_WIDTH; i++) {
for (j = 0; j < IMAGE_HEIGHT; j++) {
c = ((((i & 0x8) == 0) ^ ((j & 0x8)) == 0)) * 255;
image[i][j][0] = (GLubyte) c;
image[i][j][1] = (GLubyte) c;
image[i][j][2] = (GLubyte) c;
{
{
// Set up Texturing
// the texture wraps over at the edges (repeat)
glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_REPEAT);
glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPEAT);
// when texture area is large, bilinear filter the first mipmap
glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER,GL_NEAREST);
// when texture area is small, bilinear filter the closest mipmap
glTexParameterf(GL_TEXTURE_2D,GL_TEXTURE_MIN_FILTER, GL_NEAREST);
// select modulate to mix texture with color for shading
glTexEnvf(GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, GL_MODULATE);
// build our texture mipmaps
```

Figure 5.17 Texturing the VR scene

Also, in the display function glClearStencil() is added under glClear() . Figure 5.18 shows the shadow display subroutine in the display() function. The final virtual environment with lights, texture and shadow is shown in Figure 5.19. The situation when the lights are off is shown in Figure 5.20 where the visibility is hampered and the result looks unrealistic for rehabilitation exercises.

```
InitializeForShadows();
glColorMask(GL_FALSE, GL_FALSE, GL_FALSE, GL_FALSE);
glDepthMask(GL_FALSE);
// enable stencil buffer
glEnable(GL_STENCIL_TEST);
glStencilFunc(GL_ALWAYS, 1, 0xFFFFFFFF);
glStencilOp(GL_REPLACE, GL_REPLACE, GL_REPLACE);
//draw the plane for shadow
glPushMatrix();
Plane();
glPopMatrix();
glColorMask(GL_TRUE, GL_TRUE, GL_TRUE, GL_TRUE);
glDepthMask(GL_TRUE);
glStencilFunc(GL_EQUAL, 1, 0xFFFFFFFF);
glStencilOp(GL_KEEP, GL_KEEP, GL_KEEP);
glPushMatrix();
Plane();
glPopMatrix();
// draw the shadow of the Objects
glPushMatrix();
glColor3f(0.0f,0.0f,0.0f);
glDisable(GL_TEXTURE_2D);
glDisable(GL_LIGHTING);
glDisable(GL_DEPTH_TEST);
glEnable(GL_BLEND);
glStencilOp(GL_KEEP, GL_KEEP, GL_INCR);
glMultMatrixf(fShadowMatrix);
UEObject();
glEnable(GL_TEXTURE_2D);
glEnable(GL_DEPTH_TEST);
glDisable(GL_BLEND);
glEnable(GL_LIGHTING);
glPopMatrix();
glDisable(GL_STENCIL_TEST);
// draw the Objects normally
UEObject();
```

Figure 5.18 Sub-routine for Shadow Mapping

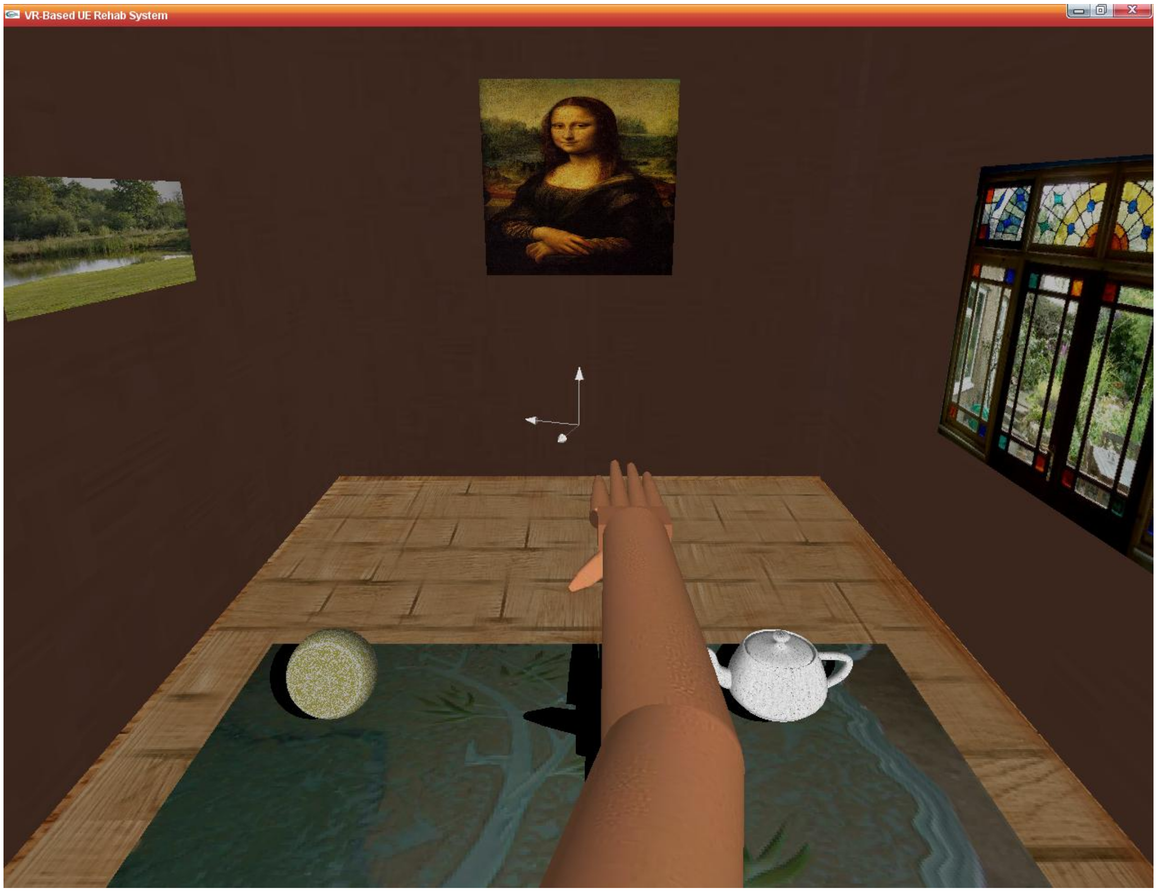

Figure 5.19 Texture Upper Extremity and Interactive VE

After modeling the upper extremity and the virtual objects, during the real time motion of the virtual arm from the motion inputs from the sensors worn by the subjects, the arm and the fingers have to be tested for any collision (detection). If the collision occurs, the grabbing task could be accomplished. Also, if the collision occurs with objects such as the table which need not be picked, the user has to avoid that path and follow a path that does not lead to undesirable collision.

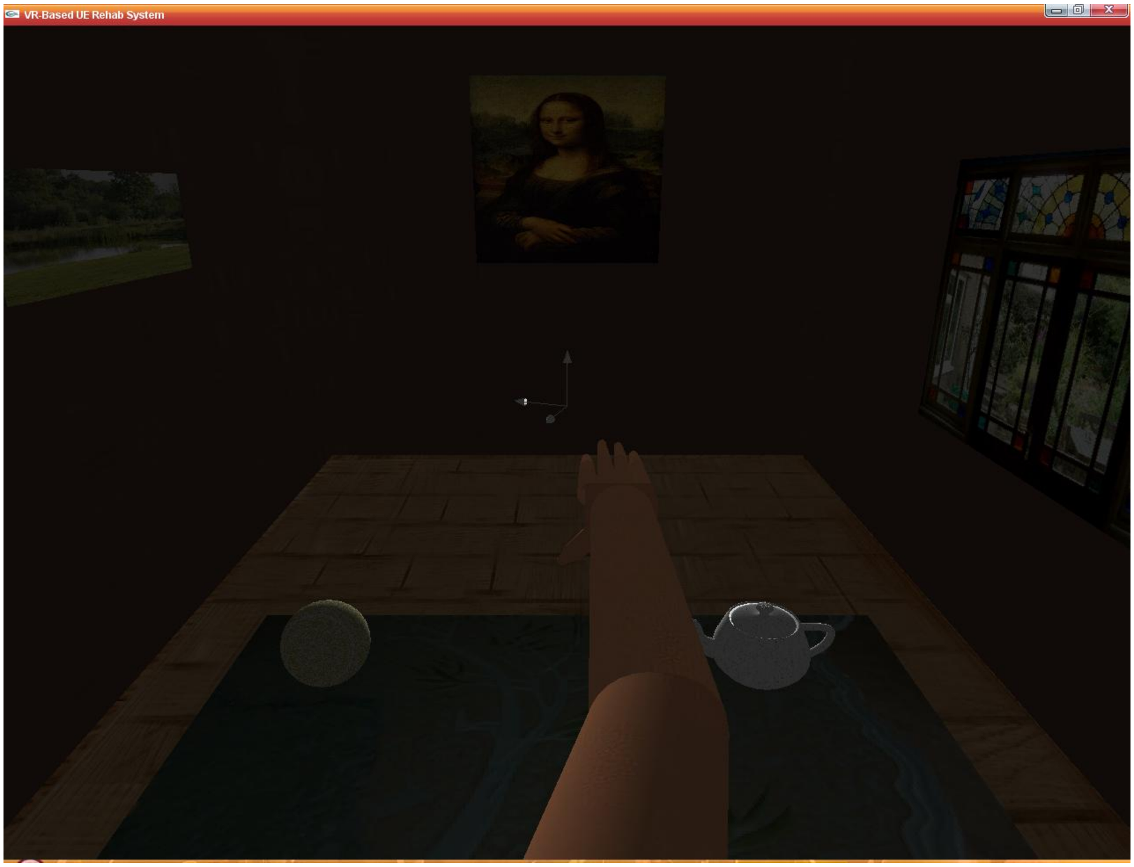

Figure 5.20 Virtual Environment with Lights Turned off

5.4.4 Collision detection

During the real time manipulation of the virtual objects their interaction often plays an important part. Collision and feedback are the two basic aspects of objects interacting in a dynamic process. Collision detection starts with the detection of intersection of objects undergoing collision and then application of appropriate equations to simulate the reaction or feedback. Once the collision occurs and the intersection testing has been undertaken, the modification of the response could be carried out either by changing the velocities of the colliding objects or other manipulation such as moving along one of the objects colliding. This in other words avoids the two objects under collision course from penetrating each other.

The main problem underlying any intelligent collision detection algorithm is the control of computational complexity involved. Computational complexity increases according to the square law with the number of vertices in the virtual environment or scene. This could also cause substantial complication. Hence in simulating a collision in the scene collision detection and feedback could take up a major share of computational power. This complexity leads to the development of advanced algorithms for collision detection.

Proximity and interference are the two main elements that are looked after in order to validate the collision during geometric collision detection. Proximity detection comes into play when the two objects simulated for collision are some distance apart from the collision course and a response is implemented whereas during interference the two involved objects are in contact thus leading to the response simulation.

Depending on the geometric handling taken into account during a specific collision simulation there are different algorithms that could be implemented. In order to reduce the complexity involved during implementation appropriate algorithms could be classified in to the following groups:

- **Bounding volumes**: Complex objects or groups of objects are enclosed within simpler volumes that can easily be tested for collisions. A bounding volume could well be represented by a hierarchy where a set of geometric objects are enclosed within a tree structure of simpler bounding objects (Yoshimoto 1992).

- **Subdivision methods**: This is an extension to the volume technique where a large object which undergoes collision is broken down into smaller objects and the hierarchical subdivision is applied. This results in more effective, faster and precise detection of the two colliding objects in the scene. A whole scene could well be constructed for collision using a subdivision method (Yoshimoto 1992, Leclercq *et al.* 2001).

- **Projection methods**: Appropriate collisions could also be evaluated depending on the projection of the virtual environment along the definitive axes or surfaces (Gudukbay 2008).

- **Proximity methods**: Allocation of the sense of location to the objects in their local axes and their collaborative detection depending on the similar geometric neighboring objects within the scene (Gudukbay 2008).

There are several approaches to collision detection that take in to account the fast moving objects interferences, as static methods could not avoid the bypassing of two objects without colliding. A sweep test detects collision between two objects when there is an overlap. In the case of faster moving objects the trajectories could be divided into small intervals where collision could be tested. There are other algorithms for collision detection that could be explored for detecting collision between the virtual upper extremity and the relevant objects in the virtual environment.

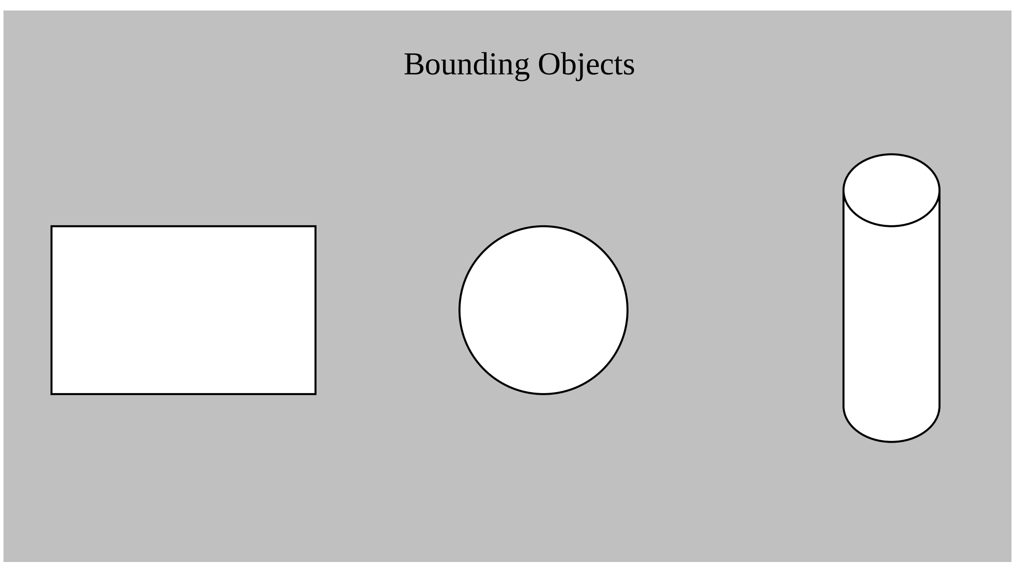

Figure 5.21 Bounding Objects commonly used for Bounding Volume collision test

To detect the collision between moving objects is one of the complex aspects of collision detection. Since the orientations of the objects are changing all the time, it becomes tedious to find the proximity between the objects. Sometimes even if the objects come in contact they penetrate through each other without detecting collision. Bounding objects are useful as they use simple objects to surround the moving hierarchical objects. They are not only used for checking collision between the complex objects but could also be helpful in rendering and picking.

The simple objects used for the bounding object collision detection are given in Figure 5.21. In our case, bounding boxes have been used to detect collision between the upper extremity and the objects. The bounding box collision detection works on the principle of tightest fitting of the bounding box to the target object involved in collision. For the two objects which are surrounded by the two corresponding boxes, their minimum and maximum vertices are derived so as to make the comparison. If the lengths are less/greater they are set inside the min/max of the vertices of the bounding boxes (Figure 5.22).

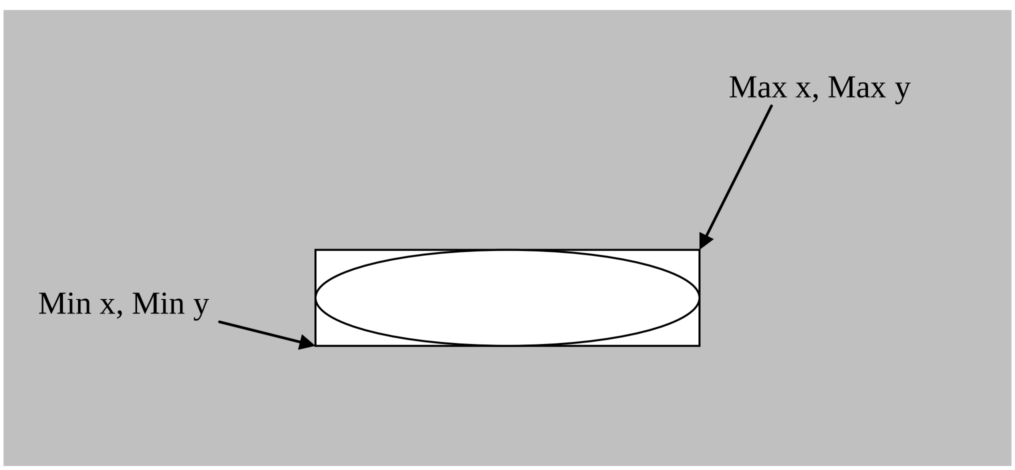

Figure 5.22 Bounding Box with the min/max vertices defined for collision test

The edges of the bounding boxes could be aligned to the world axes or they could be aligned to the local axes. The bounding boxes which are aligned to the world are defined as the axis aligned bounding boxes (ABBs) and the ones aligned to the local axes of the target objects are termed as the oriented bounding boxes (OBBs). In the case of the object changing orientation, the axis aligned bounding boxes are rescaled at each step (Figure

5.23). Collision tests are “cheaper” when considering collision tests and response using the axis aligned bounding boxes.

The x values in the minimum and maximum vertices of the two bounding boxes encompassing the two objects undergoing collision test are compared. From the separating plane perspective no collision is detected (Figure 5.23) if

Min x2>Max x1 or Min x1>Max x2.

In case this is achieved, the collision could be tested for the corresponding y and z directions simultaneously.

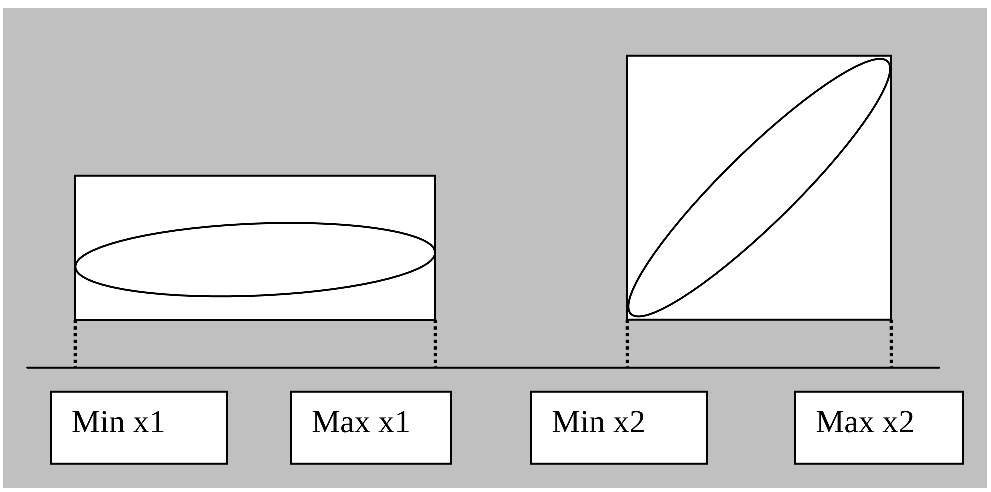

Figure 5.23 Scaling Bounding Boxes when the object changes orientation

Collision detection for objects undergoing changes in orientation could be achieved through the use of oriented bounding boxes. There boxes are aligned to the objects’ local coordinate system. These types of collision tests are much tighter, accurate faster but more expensive compared to the axis aligned bounding box tests.

5.4.4.1 An Oriented Bounding Box (OBB) Intersection Test

A drawback of using an axis-aligned bounding box is that it cannot fit rotating geometry very tightly. In our case, the upper extremity model is constantly being transformed by the rotation angles which it gets from the sensor output and is displayed as a motion sequence in the virtual environment.

There is this advantage with the oriented bounding boxes that they can be rotated to be perfectly inside the bounding volume and in the process occupies less volume than an AABB. This requires that the orientation of the box must also be specified. Figure 5.24 & Figure 5.25 shows a 2D example, where $A1$, $A2$, $B1$ and $B2$ are the local axes of boxes A and B.

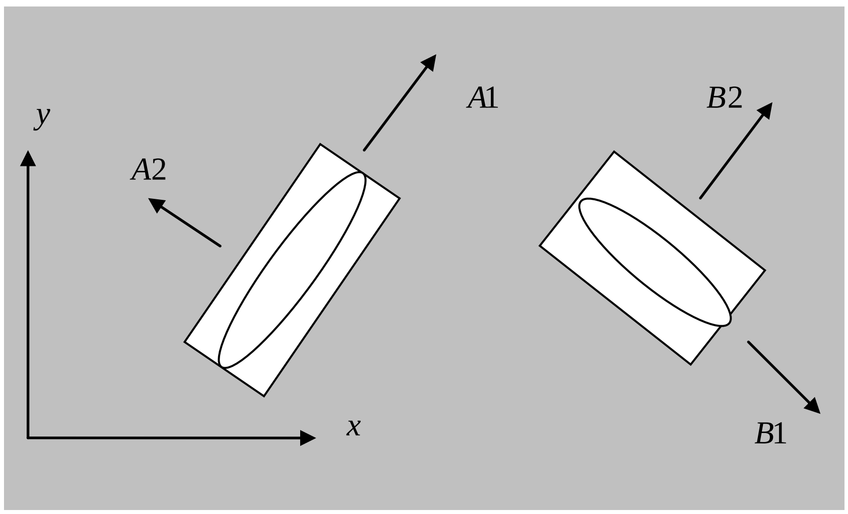

Figure 5.24 Oriented bounding boxes have local axes

For OBBs, the separating axis test must be generalized to three dimensions. A box's scalar projection onto a unit vector L creates an interval along the axis defined by L.

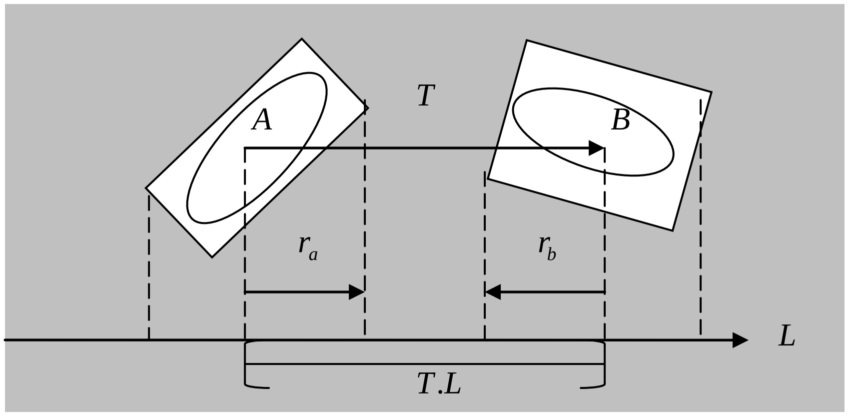

Figure 5.25 The vector L forms a separating axis

The radius of the projection of box A onto L is

$$r_a = a_1 | A^1 \cdot L | + a_2 | A^2 \cdot L | + a_3 | A^3 \cdot L |$$

The same is true for B, and L forms a separating axis if

$$| T \cdot L | > r_a + r_b$$

It can be noted that L does not have to be a unit vector for this test to work. The boxes A and B are disjoint if none of the 6 principal axes and their 9 cross products form a separating axis. These tests are greatly simplified if T and $B's$ basis vectors ($B1$, $B2$, $B3$) are transformed into $A's$ coordinate frame.

5.5 Conclusion

Exercise and training conducted alongside the visual representation and feedback could provide a long term and effective approach to rehabilitation (Sveistrup, 2004; Schettino *et al.* 2003). Physical and occupational therapists as well as subjects who are left with limited motor function with the onset of a stroke could make use of these types of systems to execute simple tasks performed with the help of a virtual guide (Cameirao *et al.* 2008, Chortis *et al.* 2008, Sveistrup, 2004).

This design of the virtual environment is followed by integrating the motion capture technology and the virtual environment for the real time simulation of the real world scenario (APPENDIX 1). Also, this basic design methodology is followed to design a specific virtual task which would be used in assessing the confidence level of the virtual environment during the execution of the tasks by healthy volunteers (see Chapter 6). The virtual arm, hand and fingers would work as a guide for the subjects to position their arm precisely before the execution of virtual tasks. Chapter 6 includes four exercises designed in the virtual environment to further assess the suitability of the VR-based system and the data from the motion sensors plus data glove will be recorded during the rehabilitation period for post analysis. Some of the data which are directly related to the research questions has been analyzed and trajectories have been plotted to validate the outcomes of the virtual training performed by the 10 healthy volunteers utilised.

CHAPTER 6. System Prototype Testing

Before the trial of the virtual reality based stroke rehabilitation system on 10 healthy volunteers and the same volunteers simulated for stroke, a physical understanding of the body planes and anatomical directions has to be understood. This chapter presents an overview of the human anatomical positions and body planes as well as the upper extremity anatomy. This is followed by the trial of the virtual reality based system and its validation by the results and feedback from the users by self report questionnaires.

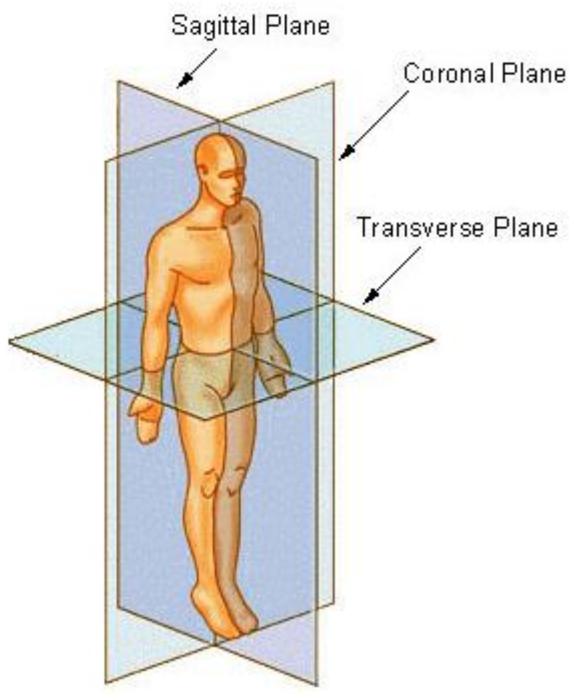

Figure 6.1 Directional Terms of Human Body (Anatomical Terminology 2011)

Anatomical directions are defined in order to locate one structure in relation to the other such as the upper arm in relation to the fore arm and hand in relation to the fingers and vice versa. Anatomical directional terms are commonly applied to the planes of the body. Body planes are used to describe specific sections or regions of the body. Anatomical position could be described as the standing, lying or sitting position with the arms hanging, palms forward. Human body could be divided in two different planes depending on the direction which is considered while looking at the human anatomical structure. A plane could be defined as a surface in which if any two points are taken, a straight line that is drawn to join these two points' lies wholly within that plane or surface. It could also be defined as the imaginary line drawn through the body to separate the body into different sections. Figure 6.1 provides a vivid view of the different body planes.

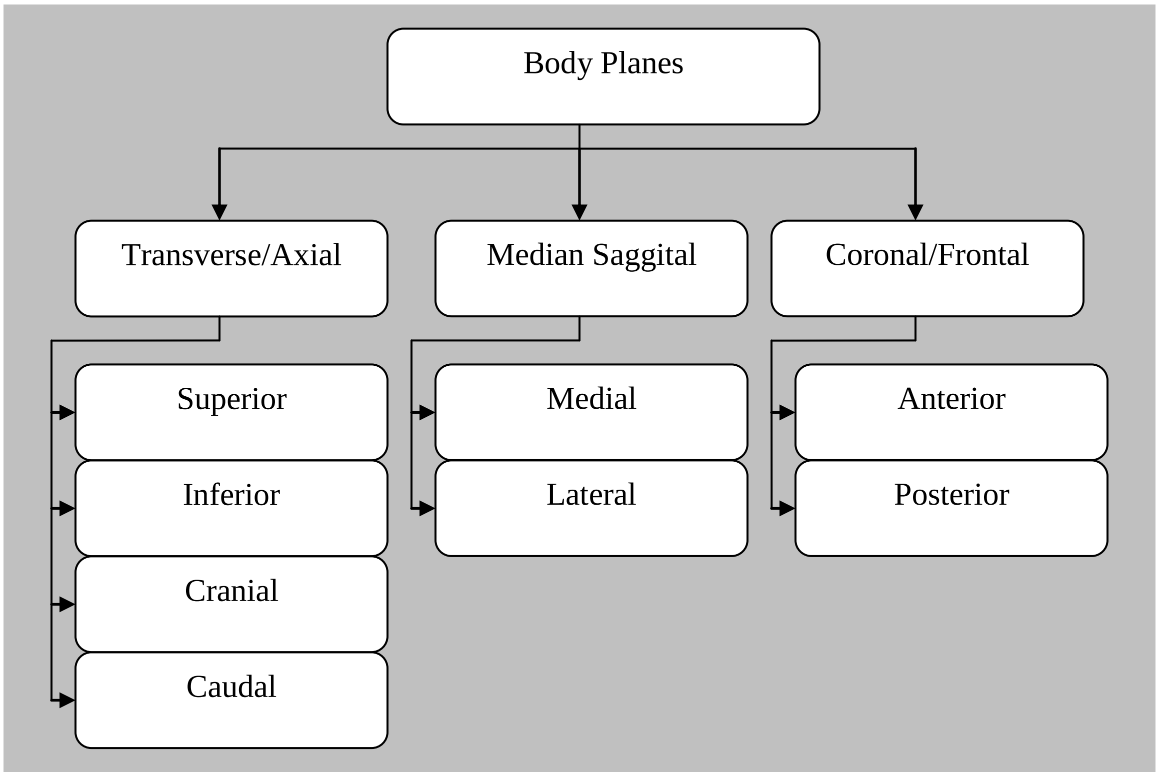

Figure 6.2 Body Planes

A flowchart describing the different body planes and its subcategories are given in Figure 6.2. The transverse planes are those which divide the body in to top and bottom half or horizontally cut the body into two halves. The body parts above form the superior while the ones below are the inferior body parts. The body parts near the head are called the cranial while the body parts located near the sacral region of the spinal column or near the tail bone is called caudal. Median planes are divided in to median and lateral where the body parts located near the middle of the body is termed as the medial and those away from the midline or the middle are termed as the lateral. Looking at the frontal plane, it divides the body into the anterior and the posterior region. Here the body parts located on the front of the body is called the anterior and the ones lying in the back of the body are called the posterior. Apart from the body planes definitions, the body point close to the point of reference are termed as proximal and the body parts away form the point of reference are termed as the distal

6.1 Anatomical structure of the Upper Extremity

Human body is a functional framework of the hard structure around which the entire anatomical system exists. Every single rigid part contained within the human body framework form the skeletal system. Joints allow the rigid and hard structure to undergo variety of movements hence behaving as an important entity of the human skeletal organization. Typically the skeleton is divided in to two parts, an axial and an appendicular skeleton.

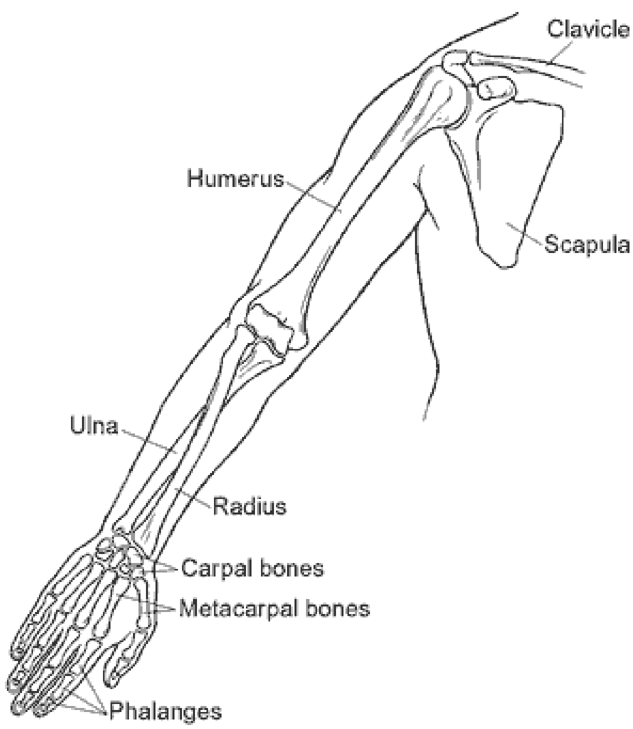

Figure 6.3 Human Upper Extremity Anatomy Bones (Hand and Micro Surgery 2011)

It is the appendicular skeleton that incorporates the skeletal structure of the upper extremity. The skeleton of each upper limb consists of 30 bones. These bones are:

Clavicle or the collar bone, Scapula or the shoulder blade, Humerus, Ulna, Radius, Carpals, Metacarpals and Phalanges Figure 6.3.

There are primarily three components which compose of the upper extremity namely the shoulder girdle, the elbow and the wrist. The upper extremity in total consists of seven joints; sterno-clavicular joint (SC) which articulates the clavicle by its proximal end onto the sternum, acromio-clavicular joint (AC) which articulates the scapula by its acromion onto the distal end of the clavicle, scapulo-thoracic joint (ST) which allows the scapula to glide on the thorax, gleno-humeral joint (GH) which allows the humeral head to rotate in the glenoid fossa of the scapula, ulno-humeral (UH) which articulates ulna on the distal end of the humerus, humero-radial joints (HR) which articulates radius on the distal end of the humerus, ulno-radial joint (UR) where both distal ends of ulna and radius join together (Kapandji 1980, Chao 1978).

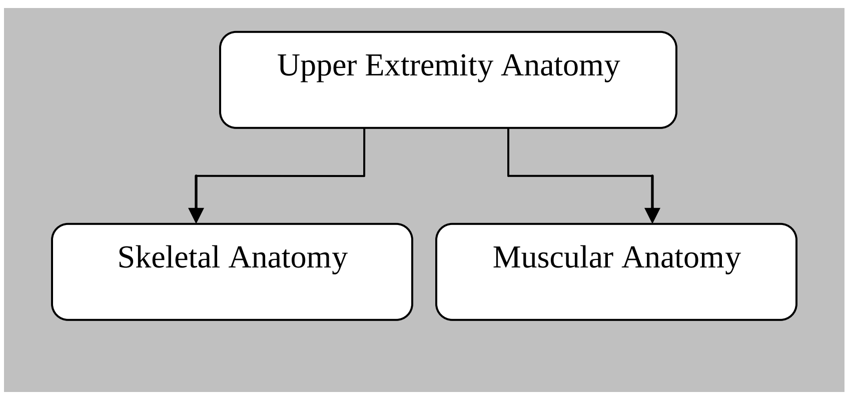

Figure 6.4 Flowchart of Upper Extremity Anatomy

If we assume the translations of the joints are negligible to their observed rotation each most of the joints can be categorised as a ball and socket joint. The scapulo-thoracic joint is an exception as it doesn't fall in to that category. The ball and socket joint allows 3 DOF rotations. When the shoulder joint undergoes rotation its movement are usually referred to as ventral/dorsal, cranial/caudal and axial rotations for the sterno-clavicular (3 DOF). Similarly when the gleno-humeral joint (3 DOF) undergoes axial rotation it represents abduction/adduction, flexion/extension. Also the medial/lateral rotation of the scapulo-thoracic joint (5DOF) causes elevation/depression, protraction/retraction, tipping forward/backward. The forearm joints observe flexion/extension and pronation/supination movements for the forearm joints (2 DOF) (Dvir 1978, Hogfors 1987).

6.2 Subject Trials

Whenever a new system is put in to place by the engineers and scientists to be used in a rehabilitation environment it has to be tested for several attributes such as safety and effectiveness. It also furnishes results as to whether the studies involved during the design of the system actually provides a more effective way of rehabilitation treatment. In our primary testing scenario our system is tested for its safety, its reliability and its effectiveness in presenting scientific observables such as accuracy, repeatability, engagement and user perspective.

Purpose

Subject trials were intended to explore the systems strength and weaknesses in order to establish its feasibility for further trial in clinical setting.

Subject ID	Age (Years)	Mean	SD
SUB1	25	28.7	10
SUB 2	16		
SUB 3	52		
SUB 4	26		
SUB 5	28		
SUB 6	18		
SUB 7	32		
SUB 8	35		
SUB 9	29		
SUB 10	26		

Table 6-1 Healthy Volunteers Demographic information

The system also gave the users an access to a simulation where they could relate their real time movements with the virtual simulation. The results from the trials were evaluated for system performance and repeatability and the ease of use in home environment.

Methods

Subjects were asked to participate in a validation purpose of the virtual reality based upper extremity stroke rehabilitation system in home setting at Bournemouth University after the Bournemouth University Ethics committee approval. Subjects who underwent trials were a selected group of 10 healthy volunteers. Each subject was included after verbal consent. The mean and standard deviations of the age of the participants are given in Table 6.1.

When selecting the participants some of the considerations were taken into account which would have compromised the participant's safety or ability to comply with the study. Participants with any neurological disorders such as uncontrolled epilepsy or ones who required an interpreter were excluded from participating in to the trial. Others with any active device implant which would result in lack of awareness of participants (eg pacemaker, implanted cardiac defibrillator, neurostimulator or drug infusion device) were also not considered for the trials. Few participants who had an allergy to sticking plaster/tape or alcohol wipes or any serious medical, psychological or cognitive impairment were also devoid of participating in to the trial of the system. Participant with any other neurological lesions which may affect the motions of upper extremity were also excluded.

Sensor Calibration

The initial calibration is done with the sensors placed on a flat surface in the absence of any metallic objects within 2 meters of diameter. In order to override the default reference with respect to which the MTx sensor outputs the orientation data, the heading direction of the sensor is set in the direction the user is facing before the training exercises. This heading could be changed to a different direction depending on the requirement of the set up of the rehabilitation training system.

The MT9 Software/SDK will calculate the orientation between the sensor reference frame, S, Figure 6.5 and the world reference frame, G. By default the local earth-fixed reference co-ordinate system used is defined as a right handed Cartesian co-ordinate system with:

- X positive when pointing to the local magnetic North.
- Y according to right handed co-ordinates (West).
- Z positive when pointing up.

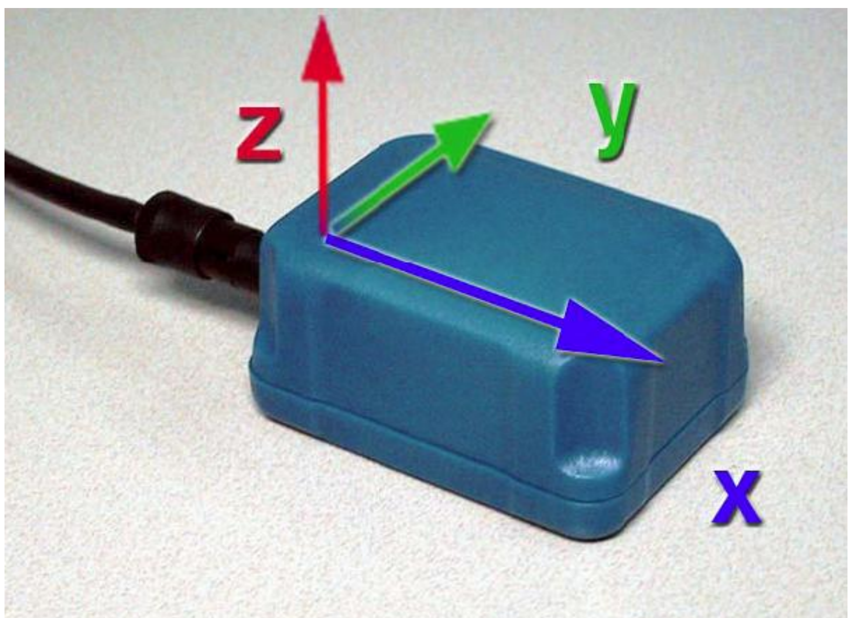

Figure 6.5. MT9 sensor body fixed co-ordinate system (Xsens Technologies, Netherlands)

The 3D orientation output (independent of output mode, see chapter 3) is defined as the orientation between the sensor reference frame, S, and the world reference frame, G, using the world reference frame G, as the reference co-ordinate system Figure 6.6.

A heading reset redefines the x-axis of the world reference frame while maintaining the Z-axis along the vertical. After the heading reset the orientation will be expressed with respect to the new world (earth fixed) reference frame Figure 6.6.

Heading reset

If it is important that the global Z-axis remains along the vertical (defined by local gravity vector), but the global X-axis has to be in a particular direction, a heading reset may be used, this is also known as "bore sighting" (Xsens Technologies, 2006) Boresight is also used to describe adjustments made to an optical firearm sight or iron sight to align the firearm barrel. By doing this there is zero drops at XY distance much faster. Similarly in telecommunication and radar engineering, antenna boresight is the axis of maximum gain.

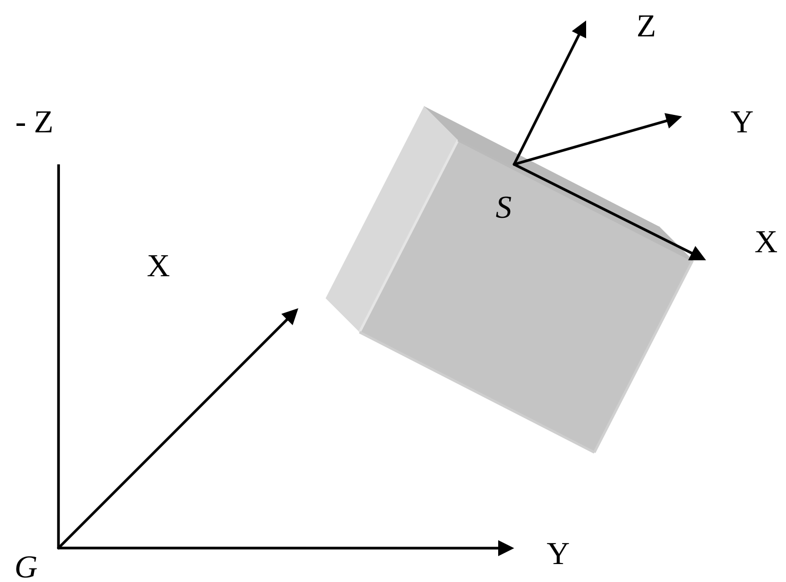

Figure 6.6: Global and Sensor Co-ordinate systems

When performing a heading reset, the new world reference frame is chosen such that the global X-axis points in the direction of the sensor while keeping the global Z-axis vertical (along gravity, pointing upwards). In other words: The new world reference frame has the Z axis along gravity, pointing upwards, the X-axis in the plane spanned by the vertical and the sensor X-axis, perpendicular to the world Z-axis and the Y-axis such that a right handed coordinate system is formed.

After a heading reset, the yaw may not be zero, especially if the MT9 x-axis is close to the vertical. This is caused by the definition of the yaw when using Euler angles, which becomes instable when the pitch approaches ± 90 deg.

A change of world (earth fixed) reference system does not have any effect of the calibrated sensor output, since the calibrated sensor output is expressed with respect to the sensor reference frame (Xsens Technologies, Netherlands).

The design of the virtual reality based upper extremity stroke rehabilitation system is based on the estimation of the wrist position in three dimensional space for carrying out the activities of daily living in a virtual world. The human shoulder, elbow and wrist together account for 17 degrees of freedom. Degrees of freedom could be defined as a set of independent displacements and/or rotations that specify completely the displaced or deformed position and orientation of the body or system. Our upper limb model has 5-DoF, 3-DoF shoulder joint and 1-DoF (elbow flexion/extension) 1-DoF (forearm pronation/supination).The glenohumeral joint or the ‘shoulder joint’ is a ball and socket joint that allows the arm to rotate in a circular fashion and to hinge out and up away from the body.

Taking in to account these specifications of the shoulder and elbow joint the reference frame definitions for sensors located on the human upper limb are categorized Figure 6. 7. The shoulder joint acted as the origin with respect to which the Euclidean distance of the wrist movement during the rehabilitation exercises has been calculated for the comparison of the movement pattern in different individuals.

To represent this 5-DoF human upper extremity a set of two inertial sensors (Xsens Technologies, Netherlands) has been used in the design. Figure 6.7 presents a schematic of the sensor mounted on the upper arm and forearm of the healthy volunteer The world Y-axis points in the direction from the left shoulder towards the right shoulder, the world X-axis points in the direction away from the body towards the extended upper limb from the shoulder, the global Z axis is perpendicular to the XY plane and points downwards from the right shoulder. Each MT9 sensor has a local axis attached to it Figure 6.7.

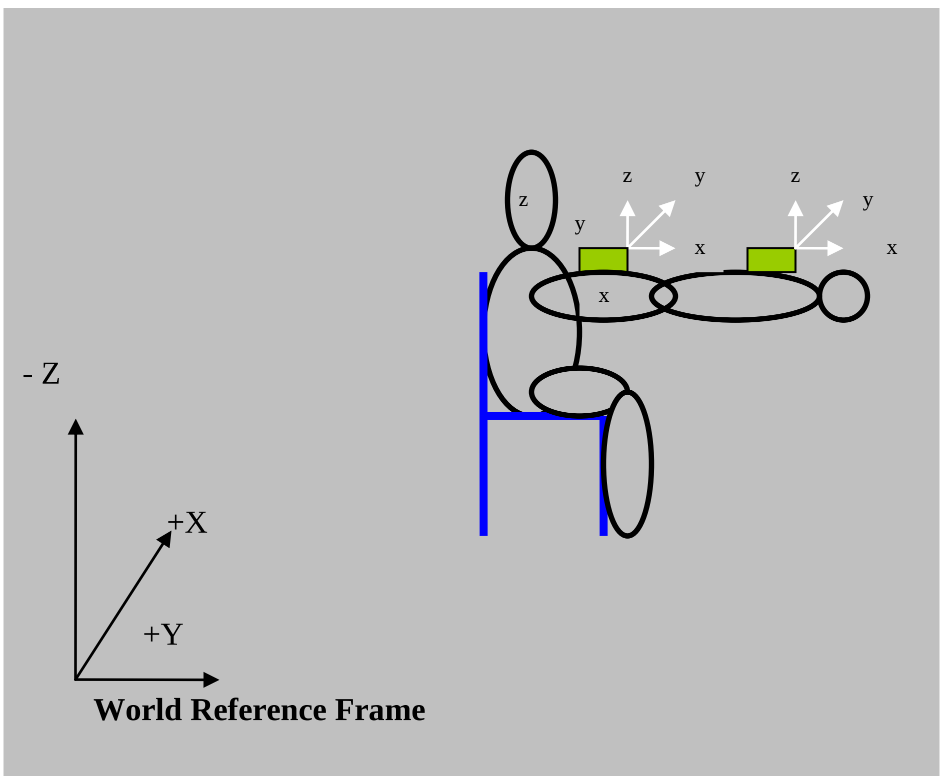

Figure 6.7: **Schematic view of the Inertial Sensor Location**

Before locating the sensors on the respective segments of the upper extremity, these sensors are calibrated. The two inertial sensors are placed on a flat surface without any motion and away from any magnetic objects (within the range of 2 meters).The Xbus Master is switched and once the sensors are identified by the specific ports, they are asked to store the new coordinate system with timestamp output enabled. The run button on the GUI is pressed and the 3D visualization of the orientation output is shown in the GUI display window. The reset button is then pressed which sets the Y axis of the MT9 body fixed coordinate system in such a way that the XYZ forms a right handed system.

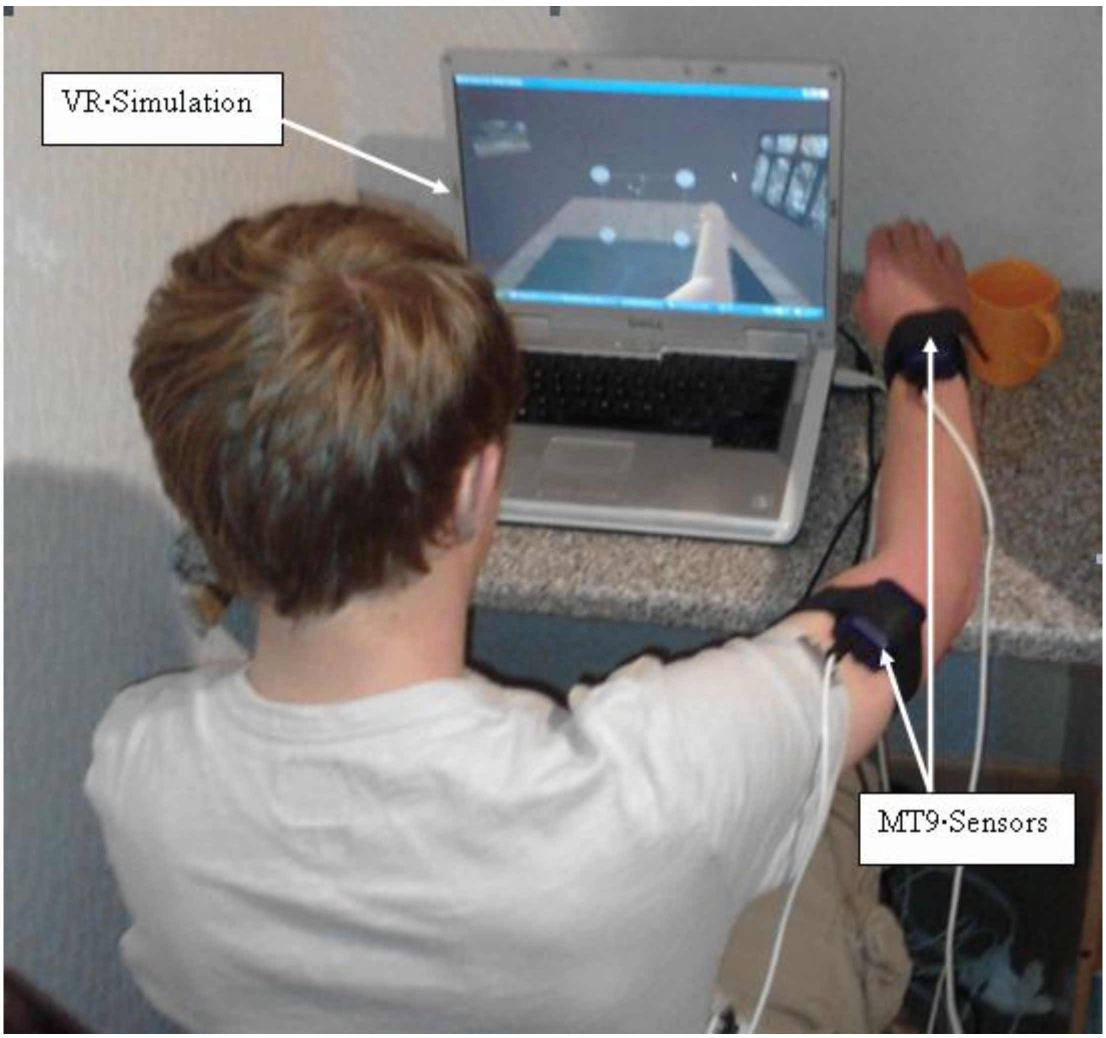

Figure 6.8A Healthy Subject Performing a VR-task in Virtual Environment

Once this calibration routine has been carried out the stop button is pressed, here the pop-up appears which asks for saving the new coordinate system which is achieved during the calibration process. The new values are saved in the Xbus Master non-volatile memory for later processing. Finally this calibration allows every sensor to align its local reference frame with the global one. Once this calibration sequence is achieved the orientation matrices provided by the sensors use the same reference to express their relative orientation.

After the orientation calibration the sensors are mounted on to the limb segments, on to the shoulder, upper arm and fore arm respectively Figure 6.8.

6.3 Calibration of the complete system with the virtual scene

The users were assisted in wearing the sensors and the DGTech virtual glove, the Xbus master is tied to their waist for the ease of wires connected to the sensor to span the movement performed by the user without any intertwining of the cables. The users were asked to be seated in a chair which was a non-swivel, stationary, high-back chair, positioned at 90 degrees upright. The chair was adjusted so that the subjects were seated with their feet flat on the floor with knee angle of 90 degrees. The table was a work table measuring 0.9 m^2.The users were asked to move their hands to four points in the virtual scene as depicted in Figure 6.8 & Figure 6.9. The coordinates of the four points in centimetres were CP1 (53, 0, 5), CP2 (53, 0, -14), CP3 (49, -22, -14) and CP4 (49, -22, 5) respectively.

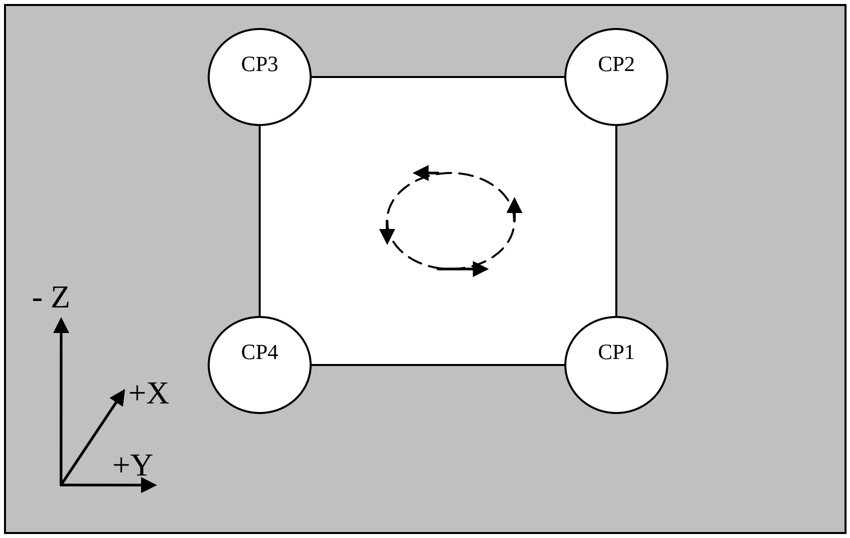

Figure 6.9: **Schematic of the calibration set up**

The subjects were asked to move their hands from an arbitrary starting position in their facing direction; the points were reached by the user in an anticlockwise direction starting from point-CP1 to point- CP4 and back to the point-CP1 before resting to a final position Figure 6.9. The calibration task was performed at a user specified convenient pace. The virtual reconstruction of the real world scenario is given in Figures 6.10 to Figure 6.14

.

The data from the arbitrary rest position has not been considered in the trajectory tracing task above. Only the motion data starting from the first point CP1 upwards to CP2 through CP3 and CP4 and finally back to CP1 has been plotted in the Figure 6.15. This was done in order to give a comparative view of the executed virtual task performed. It can be seen that SUB1 deviated about 1.5 cms away from the mean position of the four balls situated at the corner of the rectangle Figure 6.15. Though he did pass the ball but he could not control and hold his arm at the point CP3 due to fatigue hence a deviation observed in the rectangle traced by the subject. Most of the subject tried to bring their arm as close as possible to the targets (spheres situated at the corners of the rectangle) in order to move precisely through the targets. A sound was played when the subjects hit the targets and hence moved on to the next target.

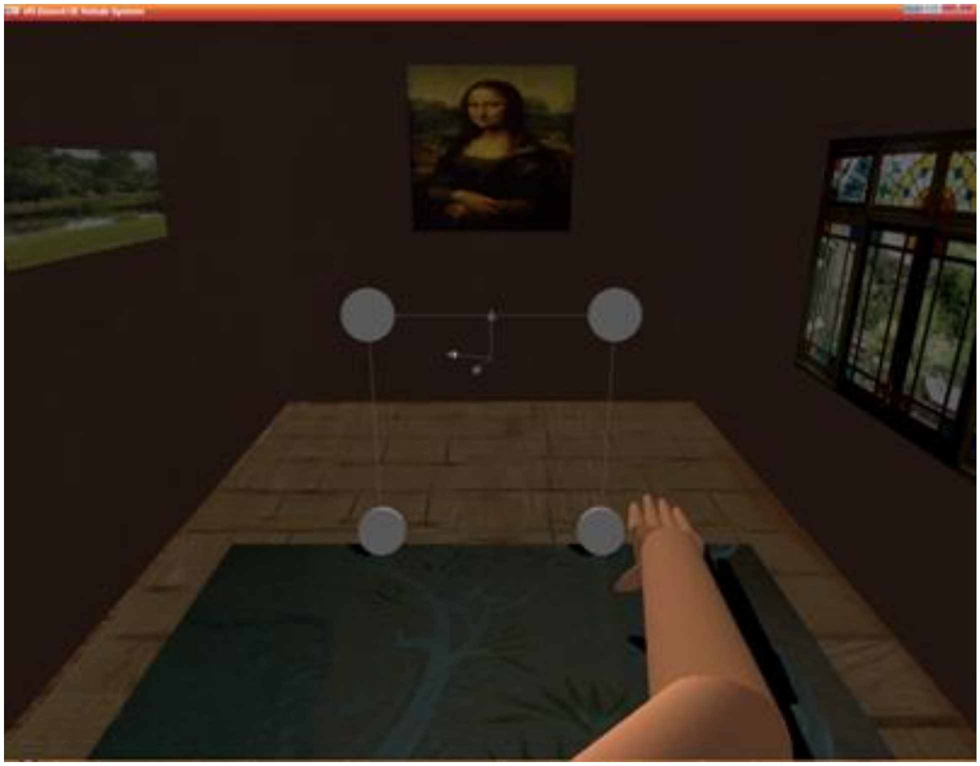

Figure 6.10: **Virtual Rendering of the Real Time Four Point Calibration**

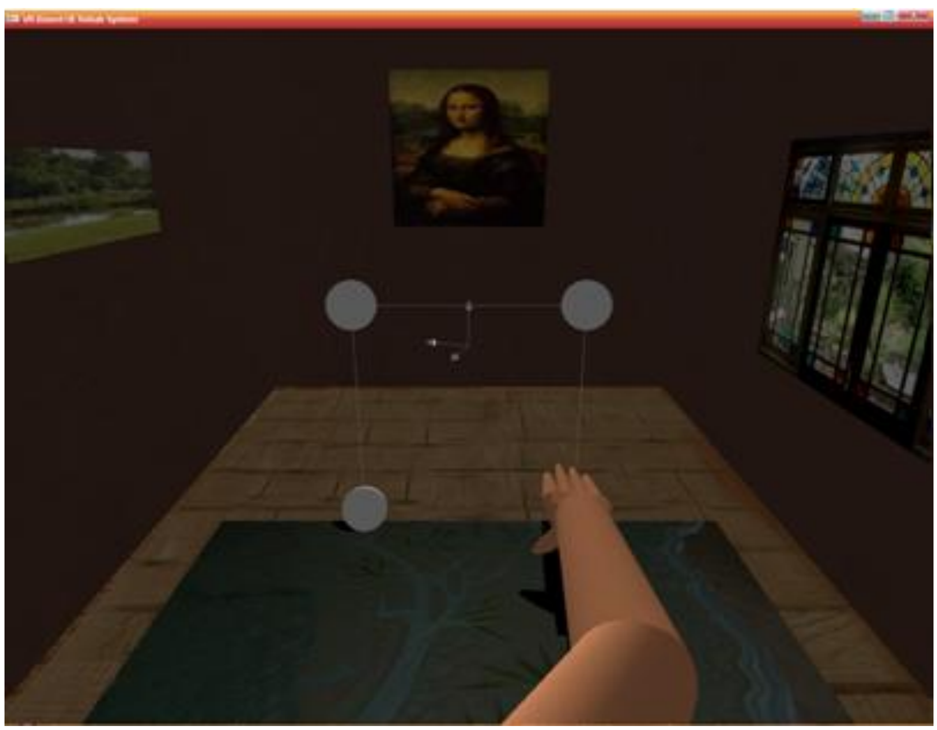

Figure 6.11: Virtual Rendering of the Real Time Four Point Calibration, Initial Position CP1

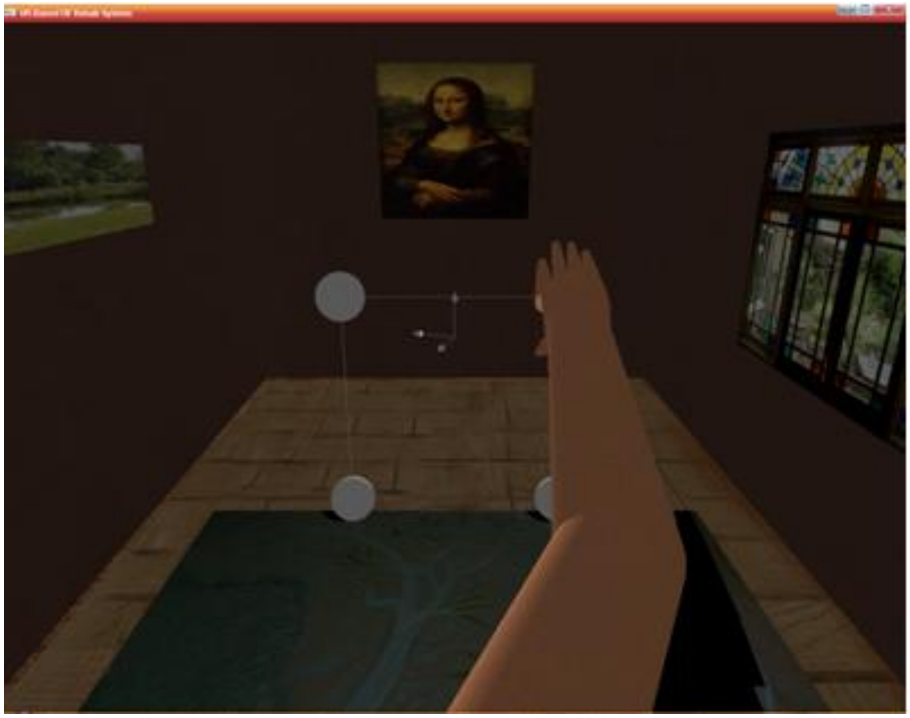

Figure 6.12: Virtual Rendering of the Real Time Four Point Calibration, Initial Position CP2

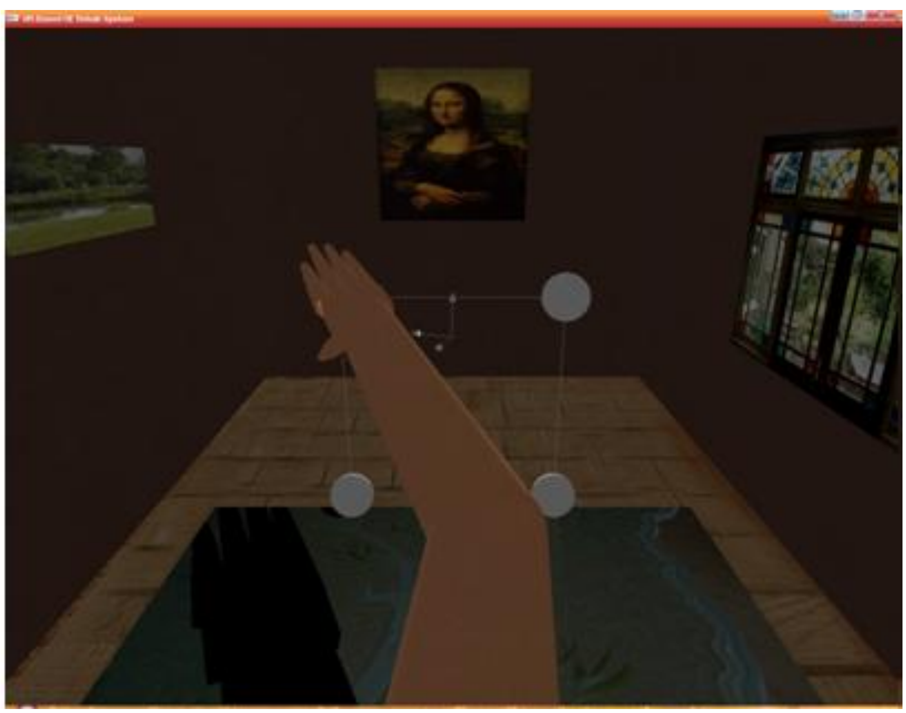

Figure 6.13: Virtual Rendering of the Real Time Four Point Calibration, Initial Position CP3

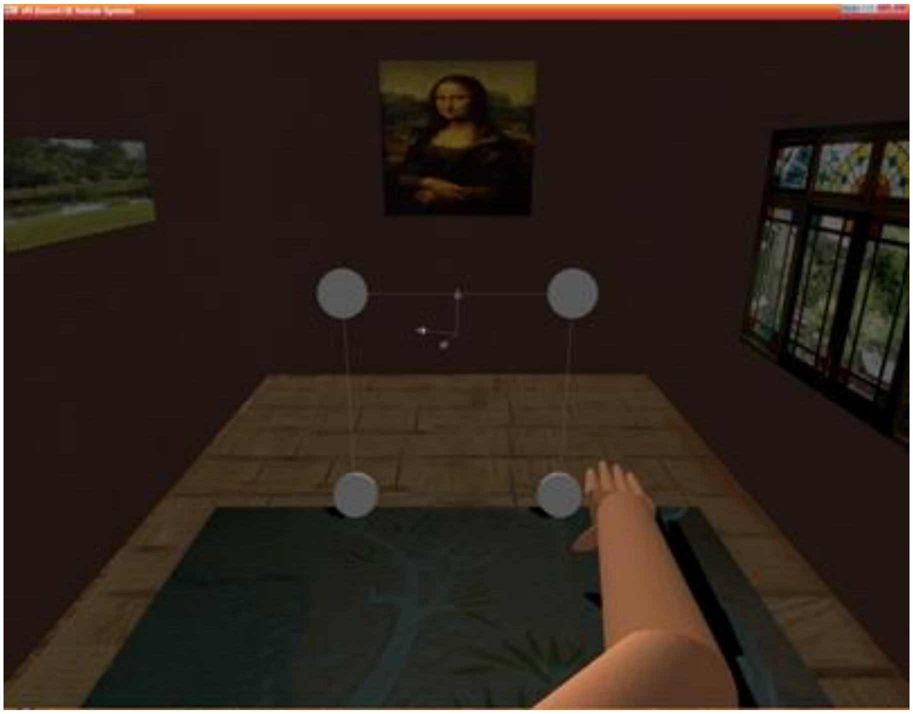

Figure 6.14: Virtual Rendering of the Real Time Four Point Calibration, Initial Position CP1

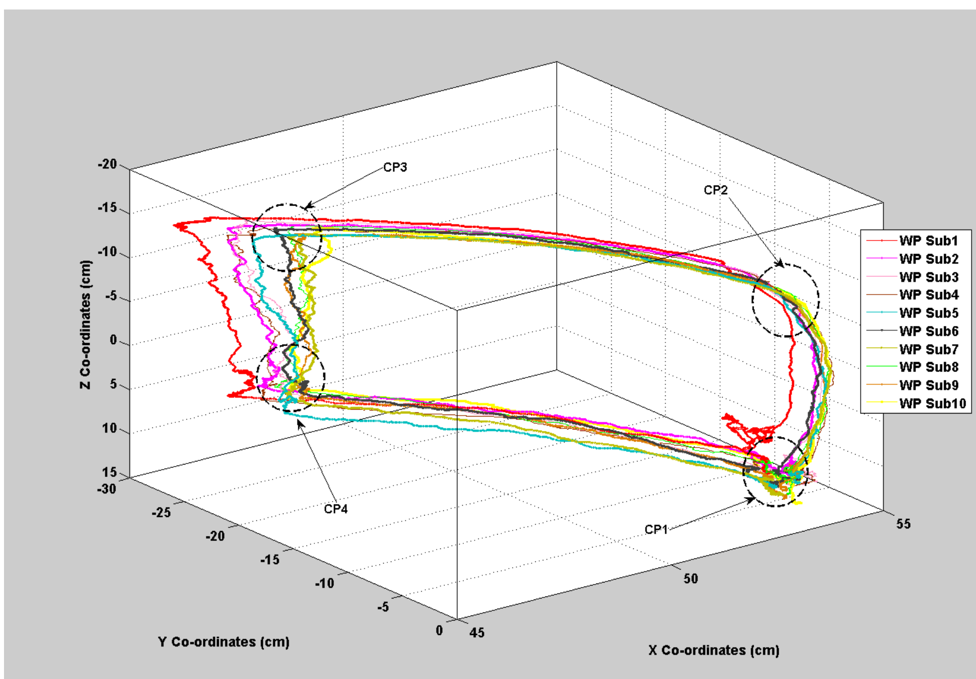

Figure 6.15: Wrist Trajectories recovered, after moving in a rectangle in the Virtual Scene

This task was also aimed at getting the user used to the virtual environment in order to perform the next level of tasks whish would use the Vhand glove for grabbing task and moving around in the virtual scene. It has been shown that stroke patients who have had experience with the a assistive technology in practicing point-to-point movements improved to a extent so that they could apply the learned sub-movements to perform untrained tasks such as drawing a circle which were smoother and accurate (Finley *et al*. 2009). This exercise is aimed at teaching the stroke patients in a goal directed training task where they would be able to learn to move their wrist to the four spheres located at the corners of the rectangle. The exercise teaches motor control and would benefit stroke patients in regaining strength in the upper extremity.

6.4 Reach and Drink Simulation

The design of the reaching task has been inspired by the researches in the past putting emphasis on the importance of functional goal which influences coordination in reaching movements both for the neurologically intact patients and healthy subjects either using the dominant hand of the affected arm (Dean *et al.* 1997, Lin *et al.* 1996, Van Vliet *et al.* 1995, Wu *et al.* 2000, Trombly *et al.* 1999, Wu *et al.* 1997). The drinking task aims at training the upper extremity actions such as reaching, grasping, releasing and manipulations. The reaching beyond the arm length is prohibited in this exercise due to the restriction of the trunk movement. In some of the researches kinematics of normal goal directed reaching have been examined to better understand the biomechanical and motor control mechanisms in healthy volunteers (Bosecker *et al.* 2010, Weiss *et al.* 2000, Maitra *et al.* 2004, Murgia *et al.* 2004). There is a growing interest in looking at the purposeful movements performed during activities of daily living (Thielman *et al.* 2008, van Vliet *et al.* 1995, Lang *et al.* 2006, Messier *et al.* 1999).

Subjects were seated at a therapy table to perform the drinking task which involved grasping of a cup located directly in front in the facing direction (from above) Figure 6.16. Reaching task consisted of three motion sequence. The subjects were asked to rest their arm at a specified fixed position on the table at RP1 (40, 18, 19) with their forearm in a pronated position; the first movement is performed to move their hand towards the target object (cup) placed at RP2 (25,-14, 9). At this position the supination of the forearm was performed to hold the cup. The final motion sequence resulted in the cup being taken close to their moth to simulate the drinking task. Bringing back the hand to the starting RP1 through the point RP2 position completed one cycle. There were 5 repetitions performed of the same task. The drinking task involved the movements of shoulder, elbow and forearm. The drinking task was executed at a self pace chosen by each subject. During the execution of the real world movement a virtual scene which had a virtual table, upper arm and the virtual cup imitated the real world scene. This helped the subjects to place their arm accurately in the scene and wherever need make adjustment to execute the drinking task. The users were free to pause and rest during the repetitions, but only after a cycle is was completed and the hand had returned to the starting point-RP1. This was advised in order to counter any deviations in the trajectory arising due to fatigue. The average time taken to complete the reach and drink task was reported to be 15 minutes.

To demonstrate the system performance the recovered trajectory of the wrist and elbow joint during the performance of the task is given in Figure 6.20-6.21.

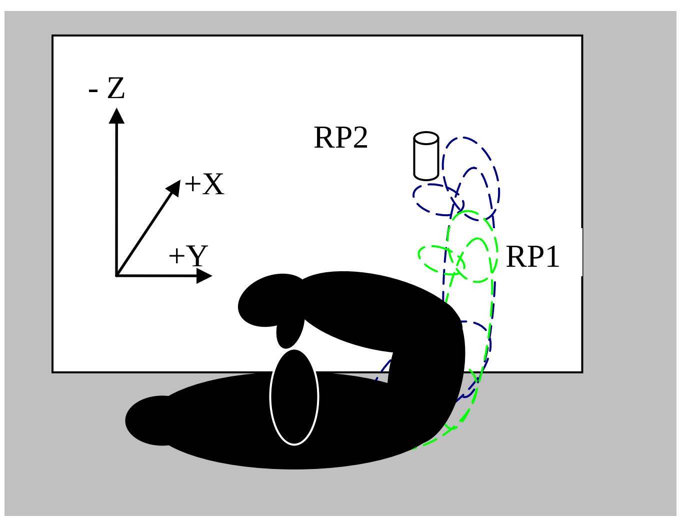

Figure 6.16: Top view of the reaching task to reach, grab and hold and reach the target which is the mouth.

The virtual reconstruction of the real time simulation of the arm during the drinking task is given in Figure 6.17 to Figure 6.19.The starting position RP1 Figure 6.17 where the hand is at rest before the start of the drinking cycle. Figure 6.18 represents the proximity of the hand with the cup and the supination of the forearm to grasp the cup. After the grasping task the hand follows a trajectory to reach the mouth. The final position where the subject reaches the mouth with the cup is rendered in Figure 6.19.

Figure 6.17: Starting Position with the hand at rest RP1

Figure 6.18: Hand Supinated to grasp the cup

Figure 6.19: The proximity of the cup to the mouth is the final orientation reached by the hand during the simulation of the drinking task

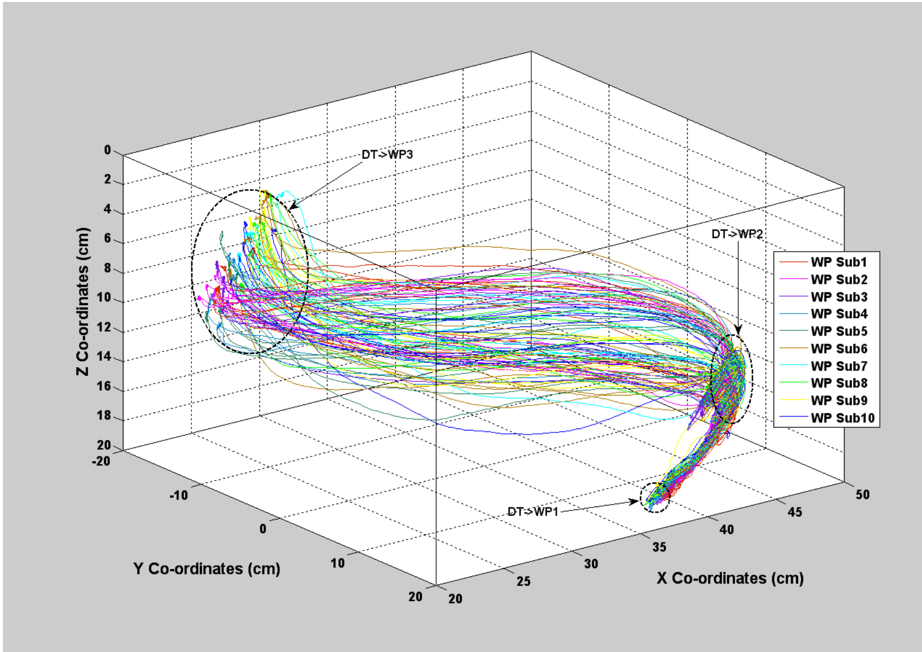

Figure 6.20: Wrist Trajectory recovered during the drinking task performed by 10 Healthy Volunteers

It can be clearly seen from the Figure 6.20, that the trajectory is smooth before and after the supination of the forearm, position DT->WP2.

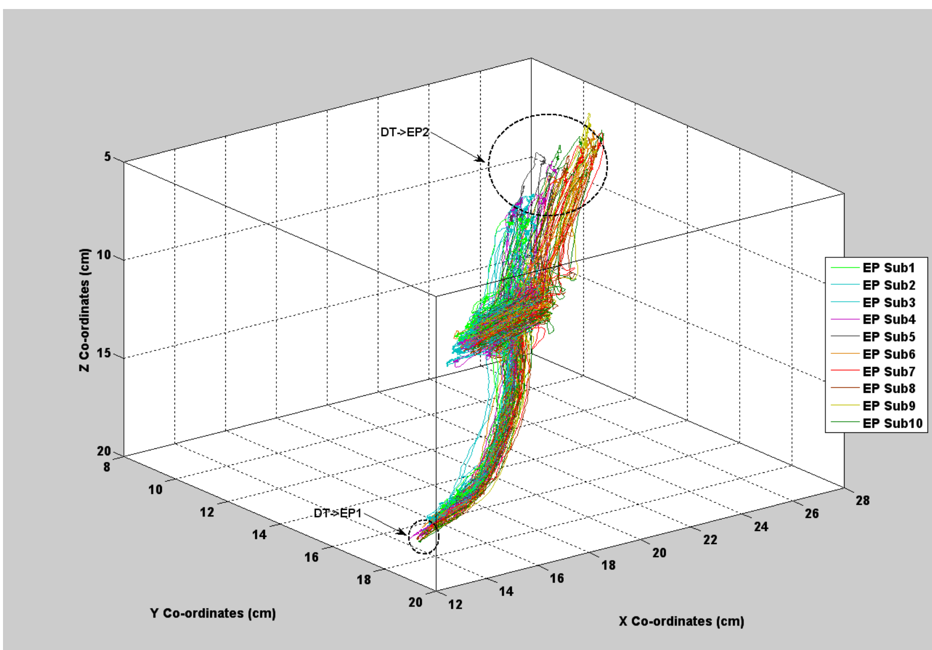

Figure 6.21: Elbow Trajectory during the drinking task performed by 10 Healthy Volunteers

As it can be seen from the trajectory Figure 6.21, that the elbow once extended towards the target (cup) upon reaching has to be elevated to execute the drinking task to completion.

6.5 Stroke simulation of the drinking Task

The developed rehabilitation system is aimed at stroke rehabilitation of the upper extremity. The system has to be tested on stroke subjects for its suitability in clinical setting. Due to the constraint on time required for ethical approval we intended to simulate a scenario where we could successfully test the viability of our system in the absence of stroke subjects. Physiotherapists were consulted and their suggestion resulted in immobilising the movements of the upper extremity of the healthy volunteers by some sort of splint like movement restraint brace. Two plastic brace segments were used for the same purpose. The first brace segment was used for the upper arm and the second was used for the fore arm. The two braces were linked together by a elbow flexion/extension restraint made of plastic. The pronation/supination of the fore arm was restrained by a scale put under the forearm brace.

At the beginning of the trials healthy volunteers they were asked to wear a splint that restrained their arm movement and limits the range of motion of the upper extremity Figure.6.22.

The range of movement of the upper extremity is given as the wrist position and elbow position during the training task. The wrist positions are given in Figure 6.23. And the elbow positions are given in Figure 6.24. It can be clearly seen from the trajectories that the average Euclidian distance of the wrist from the origin is much less than the one without the splint. Also during the reach and grab activities to drinking simulation, the fore arm does not undergo significant pronation/supination as in case of Figure 6.20, point DT->WP2 where the hand reaches the cup and after significant supination the same drinking task is executed before returning back to the pronated fore-arm position and back to the initial position DT->WP1.

Comparing the end positions reached in Figure 6.20 (DT->WP3) and the Figure 6.23 (SS->WP2), it is readily visible that the healthy volunteers without their movement constraints reach closer to their mouth than when they had their movements constrained.

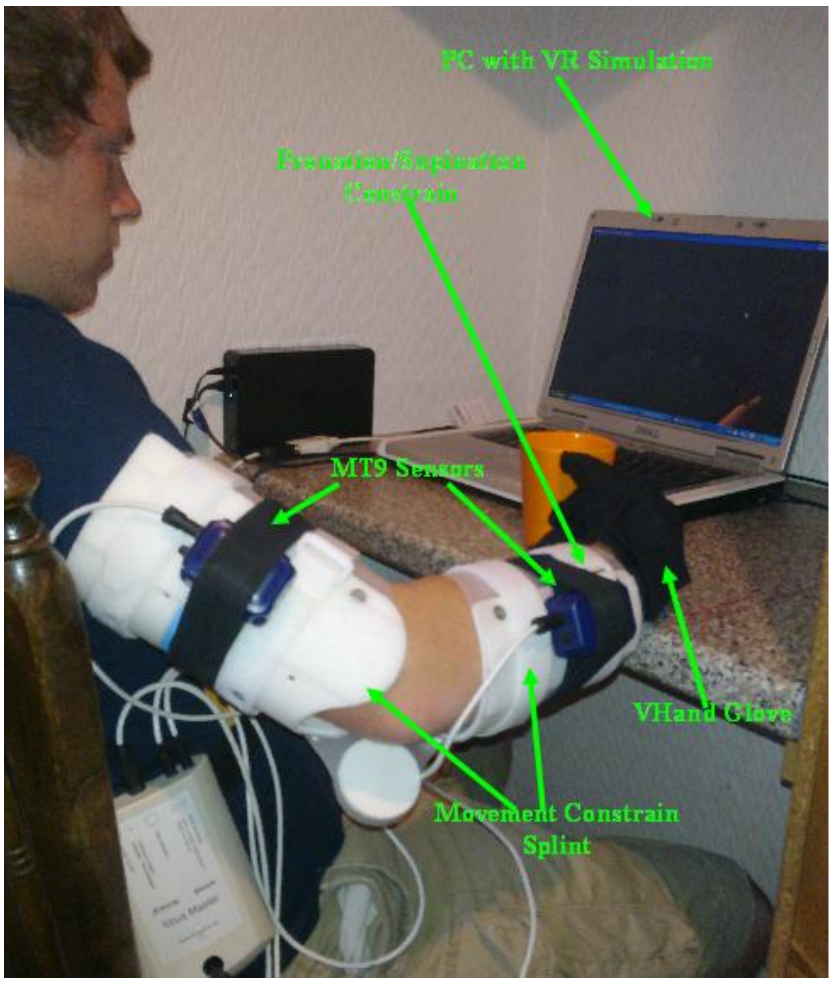

Figure 6.22Subject performing the VR-task with the constraint on

Also, they started from a starting position which was closer to their body Figure 6.20 (DT->WP1) when without the splint, but in case of the constraint movement they started at the position of the cup which was situated farther away from the body.

It can be observed from the Figure 6.24 that during the stroke simulation using the splint; the elbow does not trace a smooth trajectory. This is due to the restriction of the upper arm and shoulder to a point where the shoulder does not under a significant angular rotation as in case of Figure 6.21, where it can be observed that the elbow is elevated from a initial position (DT->EP1) which is much lower in range to a much higher position when the hand meets the mouth (DT->EP2) during the drinking simulation.

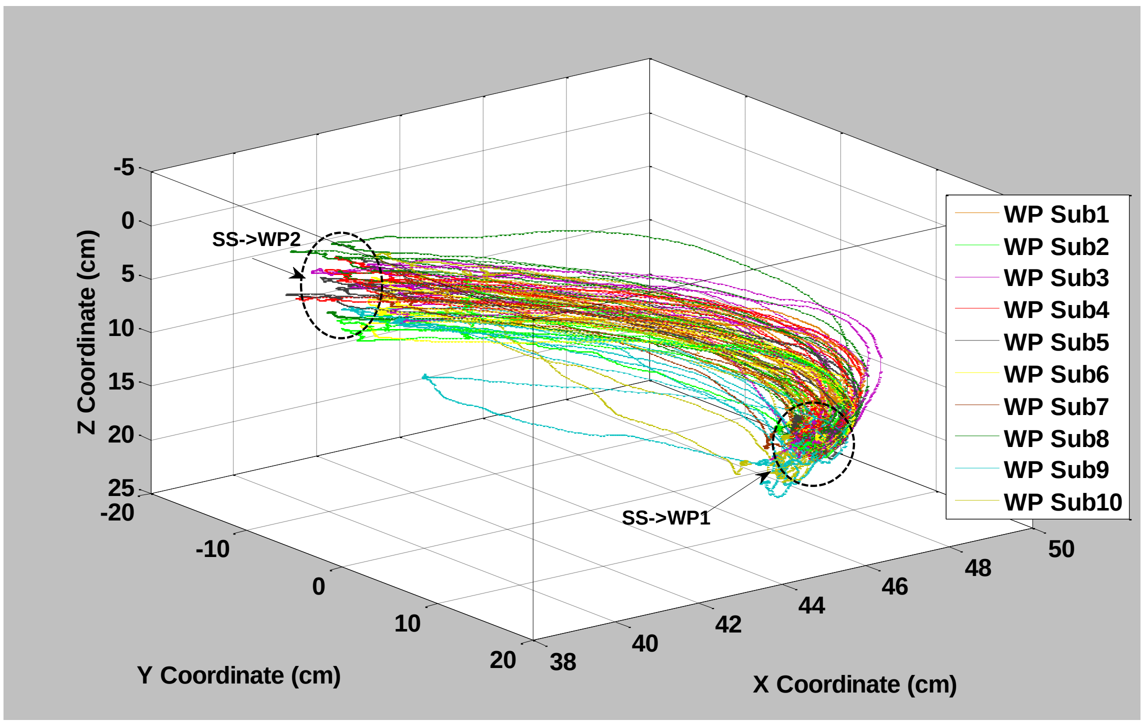

Figure 6.23: **Wrist Positions as observed during the simulation of the movement constrain**

The results were obtained from the healthy volunteers participating in the VR simulation exercises as well as the same volunteers undergoing restricted pronation/supination motion of the fore arm. Euclidean distances from the origin situated at the shoulder were calculated. The two Euclidean distances calculated for each subject during the trial with and without the splint are down sampled (reducing size of the orientation data).

The down sampled data are examined for correlation (how closely the volunteer's motion differs or is related during their upper extremity in motion). The correlation is examined only for the orientation recorded during the upper extremity in motion, both for the healthy volunteer and the stroke simulated volunteers. The comparisons of the Euclidean distance measured for their correlation coefficient are given in Table 6.2 to Figure 6.11. Correlation coefficients are higher which shows that the trajectories obtained are closely related during the drink task. But it could be observed from the Figure 6.25 and Figure 6.23 that the range of motion for the simulation of the subject with and without the splint varies for each subject. The healthy volunteers with the splint on have trajectories which are smaller in length than those without splint. Also from the Figure 6.20 it can be seen that there is pronation and supination observed at the point when the cup is grabbed where as in Figure 6.23 there is no prononation/supination due to the constrain from the splint.

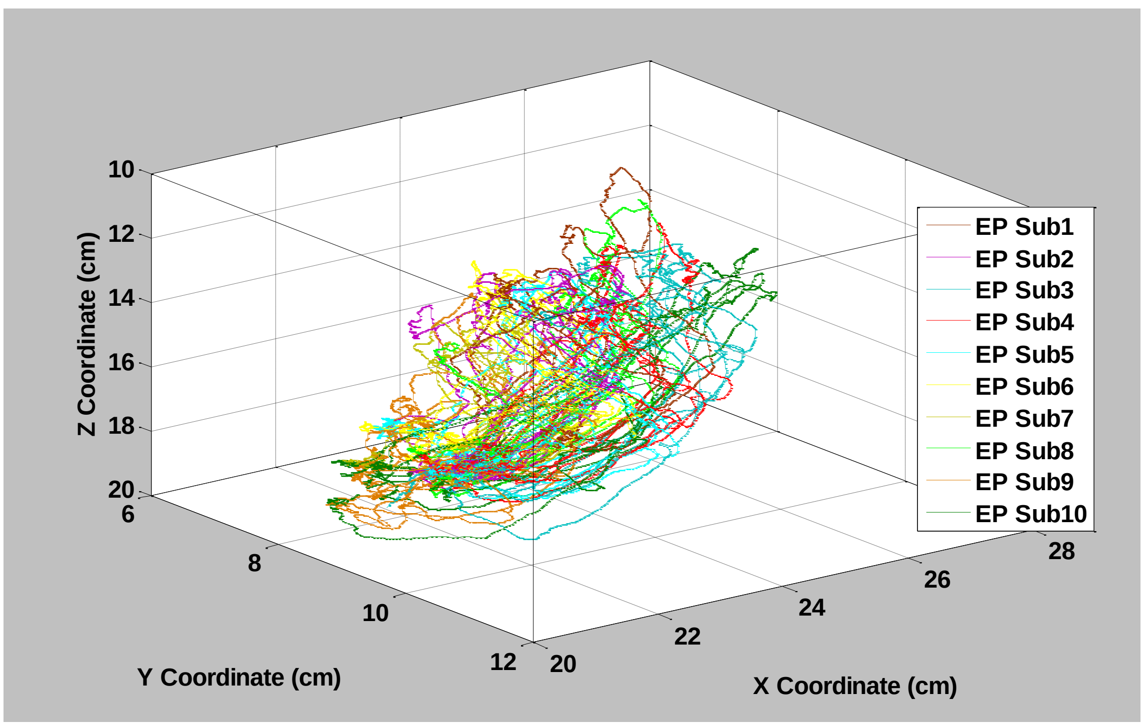

Figure 6.24: Elbow Positions Observed during the Simulation of the Drink Task with movement constrain splints

There is a continuous trajectory and there is no supination observed Figure 6.23. The subjects with the splint were not able to reach their mouth and were also not able to rest their arm at the starting position as in case without the splint Figure 6.20.

The correlation coefficient of the Euclidean distance calculated for pair of subjects with and without splint is given in Table 6.2-6.11. Each subject performed 5 experiments and the individual experiments have been taken in to account for each subject to calculate the correlation coefficient. The experimental data suggests that the trajectories were taken into account for the duration of time when the subject hand was in motion, but not at rest. So the data of the subject at rest has been discarded by down sampling (reducing size of the orientation data) and only the movement data has been taken in to account for the correlation calculation.

Table 6-2: Subject 1 Correlation

Experiments Number	Correlation Coefficient
1	0.9438
2	0.8511
3	0.9923
4	0.9583
5	0.9968

Table 6-3: Subject 2 Correlation

Experiments Number	Correlation Coefficient
1	0.9930
2	0.9802
3	0.9947
4	0.9728
5	0.9980

Table 6-4: Subject 3 Correlation

Experiments Number	Correlation Coefficient
1	0.9954
2	0.9929
3	0.9791
4	0.9759
5	0.9632

Table 6-5: Subject 4 Correlation

Experiments Number	Correlation Coefficient
1	0.9981
2	0.9505
3	0.9762
4	0.9984

5	0.9898

Table 6-6: Subject 5 Correlation

Experiments Number	Correlation Coefficient
1	0.9650
2	0.9981
3	0.9946
4	0.9532
5	0.9932

Table 6-7: Subject 6 Correlation

Experiments Number	Correlation Coefficient
1	0.9836
2	0.9543
3	0.9561
4	0.9754
5	0.9959

Table 6-8: Subject 7 Correlation

Experiments Number	Correlation Coefficient
1	0.9528
2	0.9953
3	0.9971
4	0.9753
5	0.9916

Table 6-9: Subject 8 Correlation

Experiments Number	Correlation Coefficient
1	0.9975
2	0.9983
3	0.9971
4	0.9642
5	0.9973

Table 6-10: Subject 9 Correlation

Experiments Number	Correlation Coefficient
1	0.9796
2	0.9879
3	0.9919
4	0.9917
5	0.9541

Table 6-11: Subject 10 Correlation

Experiments Number	Correlation Coefficient
1	0.9416
2	0.9968
3	0.9983
4	0.9584
5	0.9938

To estimate the similarities and differences between the subjects without the splint and with the splint repeated measure ANOVAs test has been conducted (IBM 2011). The p value for testing the significant difference between healthy subjects and stroke simulated subjects with the splint on is 0.000 which suggest that there is significant difference between the measured Euclidean distances. These were the 3D distances were measured from the origin situated at the shoulder to the end point (wrist), since wrist joint was used to manipulate the virtual objects in the scene. Similarly p values for testing the difference between subjects is very less 0.000.

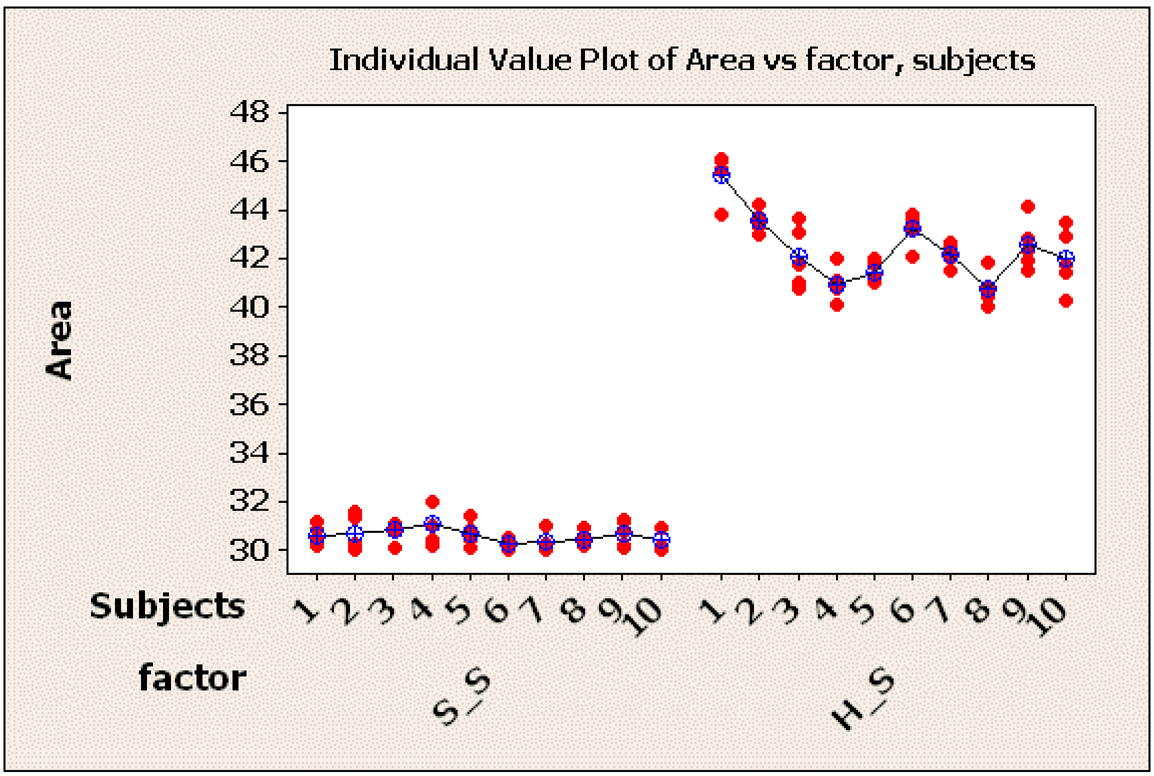

Figure 6.25Comparison of Area under the Curve showing Euclidean distances for Healthy and Stroke Simulated Volunteers

This means that all the subjects are also significantly different. In the Figure 6.25 red dots are the numbers of repetitions for each subject for 10 subjects, which is plotted against the area $(cm)^2$ under the wrist (3D Euclidean Distance measured from the shoulder as the origin) which was measured as the Euclidean distance from the shoulder (0, 0, 0). The Euclidean distance was chosen as the statistical baseline for comparing subject's movement in 3D space. S_S stands for the stroke simulated patient where as the H_S stands for the healthy subjects. It could be seen from the figure that there is a significant difference (+/- 10 cms) between the area carved by the healthy subjects without the splint and with the splint. The subjects with the splint on (S_S) could cover lesser area with respect to the healthy subject's (H_S). There is also a significant difference (+/- 3) within subjects for healthy subjects (H_S) during the reach and drink task. The area which has been considered for the ANOVAs test are the ones when the upper arm is in motion, the area carved when the hand is at rest has not been considered to avoid any ambiguity ins results.

6.6 Vertical Pick and Place

There was an interval between the first and the second task. Users were encouraged to take some rest and walk around in order to start over again. Once the sensors and the gloves were sworn by the users after the average resting time for each being 8 minutes, the users were willing to take on the second test. The second test comprised of a simple movement of the upper arm and the forearm in the vertical plane which lied in the anterior frontal plane of the body Figure 6.26. This task did not include any interactions with the real world objects. The subject's upper extremity orientations data was fed in to the virtual scene where after the position estimation the interaction of the virtual hand was achieved by the virtual objects. The complete test was conducted in the virtual environment. The subjects were asked to reach the virtual ball placed at a point VBP1 (52, 0, 16) from an arbitrary starting position at a self selected pace Figure 6.26. Once their hand reached to a closest proximity of the virtual ball, they were advised to grasp it.

Once the grasping was complete the subjects were encouraged to raise their hand as straight as they could without any strain on their shoulder and place the virtual ball in to a virtual square situated at a point VBP2 (52, 0, -16) Figure 6.26. After the ball has been placed in the virtual square, the subjects brought their hand back to the starting position following closely as straight a path as they could trace.

When the user reaches the first objects which is on the lower ground its colour changes that means the collision is detected and the object could be held in the hand. There is little movement in the y-direction hence, only x and z coordinates are displayed in Figure 6.31 & Figure 6.32.

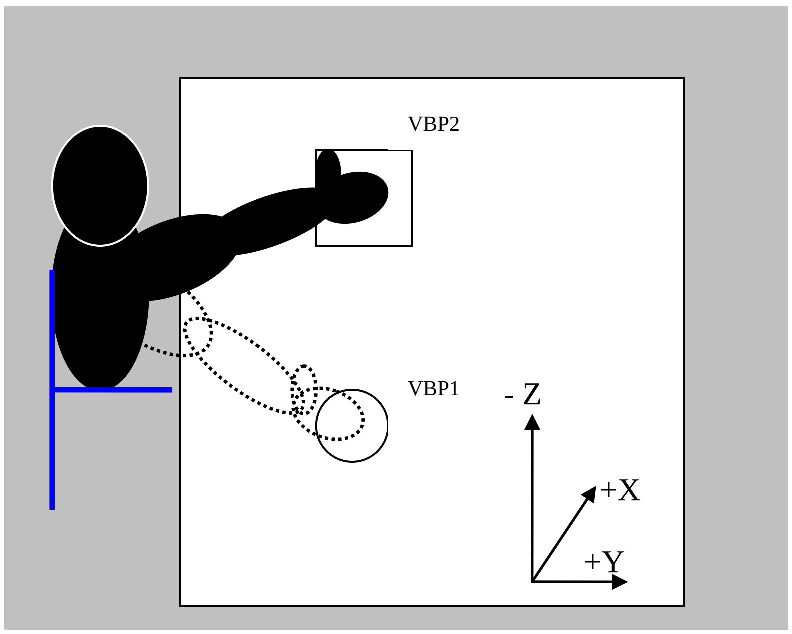

Figure 6.26: Side View of the Vertical Pick and Place Task

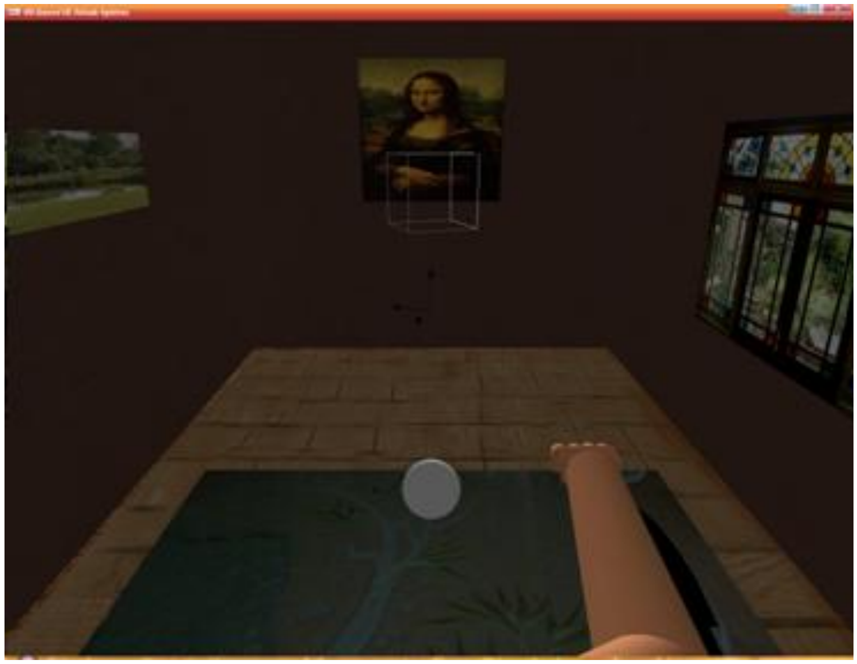

Figure 6.27: **3D reconstruction of the Subjects real time movement**

Figure 6.28: **3D reconstruction of the Subjects Ream time movement during the vertical grab, hold and reach task**

Figure 6.29: **Mid way through the horizontal exercise, in the saggital plane**

Figure 6.30: **Final Movement in reaching movement during the horizontal movement**

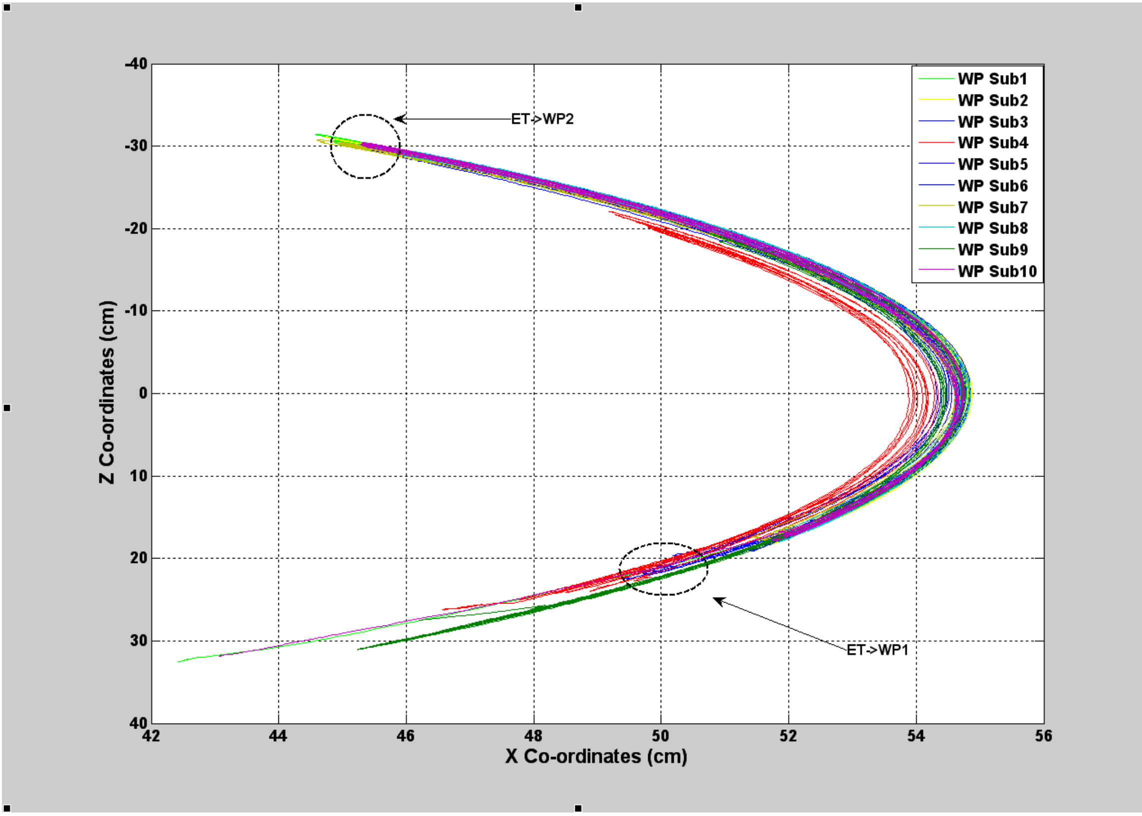

Figure 6.31: **Wrist Trajectory obtained during the vertical pick and place task**

The user then is asked to take the object to the final position which is on the higher ground. The user then drops the object and comes back to the original position following the straight line. The same task is performed again and reaching, picking the object dropping it to the goal and returning back to the initial position is the completion of a cycle. Five repetitions are performed in order for the data to be statically significant. The trajectory recovered during the execution of the task is provided in Figure 6.31 & Figure 6.32. The virtual reconstruction of the trajectory is provided in Figure 6.27 to Figure 6.30.

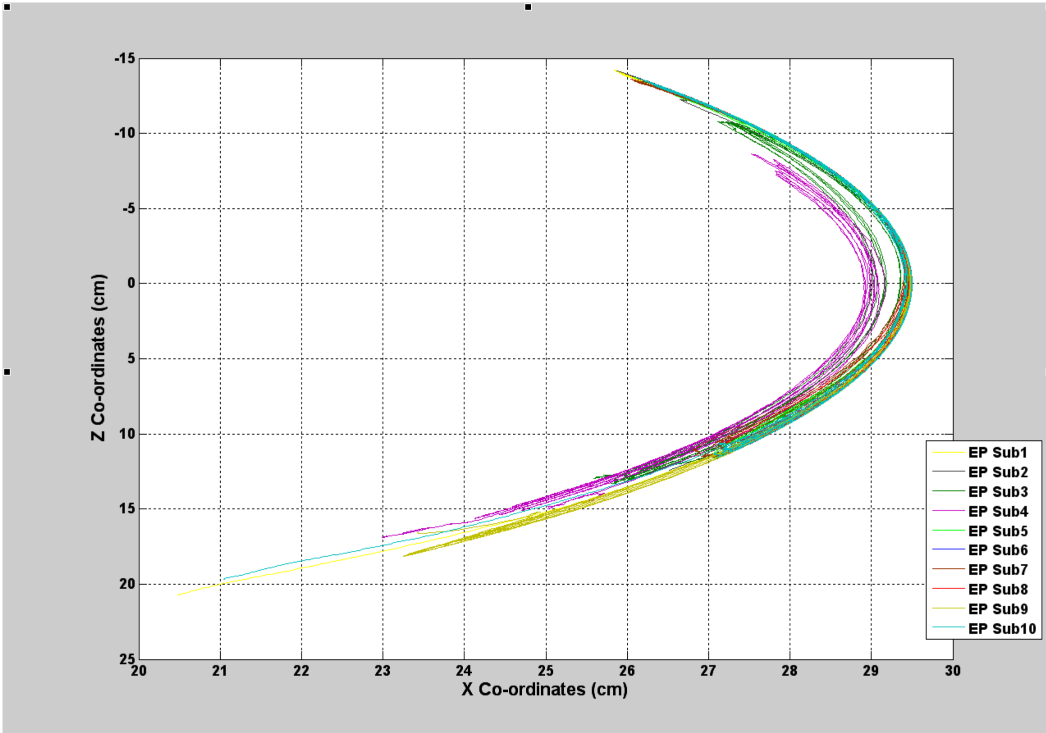

Figure 6.32: **Elbow Trajectory during the vertical pick and place task**

The average Euclidean distance calculated is 53.87 cms from the origin located the shoulder joint for each subject. This shows a consistency in the movement patterns observed by all the volunteers during the execution of the virtual task. The mean and standard deviation of the Euclidean distance of the wrist are given in Table 6.12

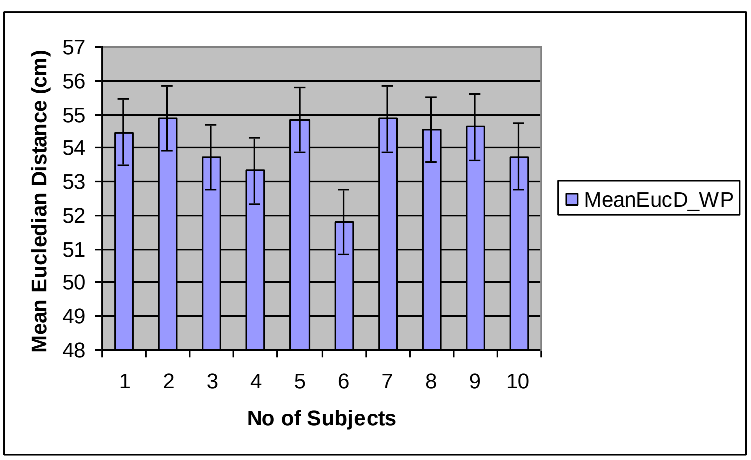

Table 6-12: **Mean Euclidean Distance with their standard Deviations**

During the execution of the vertical pick and place task there is an error of +/- 2 cms in the Z and X directions. It can be seen from the Table 6.12, that there is no significant difference within subjects during the execution of the horizontal pick and place task. The significant difference between the means for 10 healthy subjects is seen to be 3 cms. The significant difference could be due to different picking position for different subjects (some picking the virtual objects close to the center of the object, some picking at the object's boundary). Also, the virtual guide where the users could relate their movement as closely as possible would have motivated them for removing any abnormality in the trajectories over the 5 repetitions.

6.7 Horizontal Pick and Place

This task is focused on the internal external rotation of the shoulder. Two points in the virtual environments are identified which are joined by a virtual line parallel to the virtual table. The user is asked to move to point-1 which lies to the right of the centre of the virtual scene. When the colour of the objects changes to red that means that the feedback is obtained upon the collision of the virtual hand/fingers with the virtual objects. Once the objects are grabbed the user is asked to move the object to the final position point-2 keeping the upper arm and fore arm parallel to the table in the real world. The top view of the exercise is shown in Figure 6.33. If any deviations due to fatigue occur during the task execution the virtual arm deviates from the predefined trajectory. Users are encouraged to correct their wrist and elbow position in order to provide better projections of the real arm movements in the virtual environments. This also makes the collision detection easy and improves the accuracy which results in better trajectory. The trajectory of the wrist and the elbow recovered during the execution of the Horizontal pick and place task is provided in Figure 6.38 & Figure 6.39.

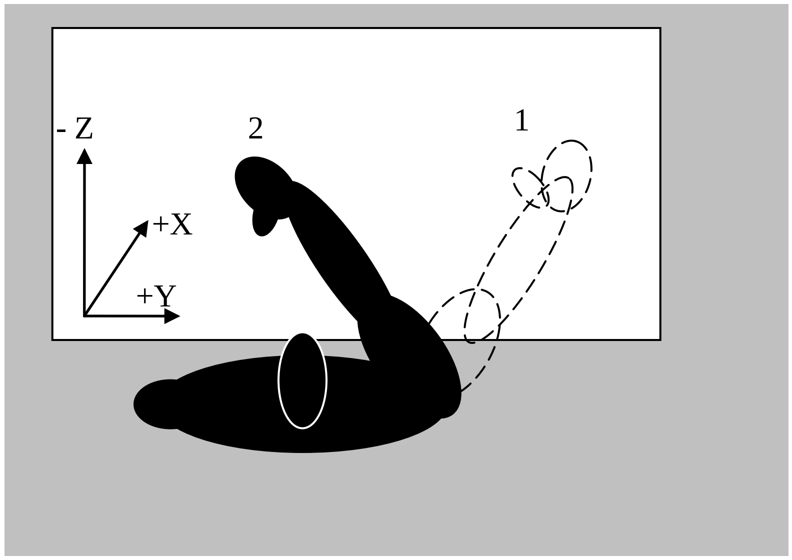

Figure 6.33: Horizontal Pick and Place Task

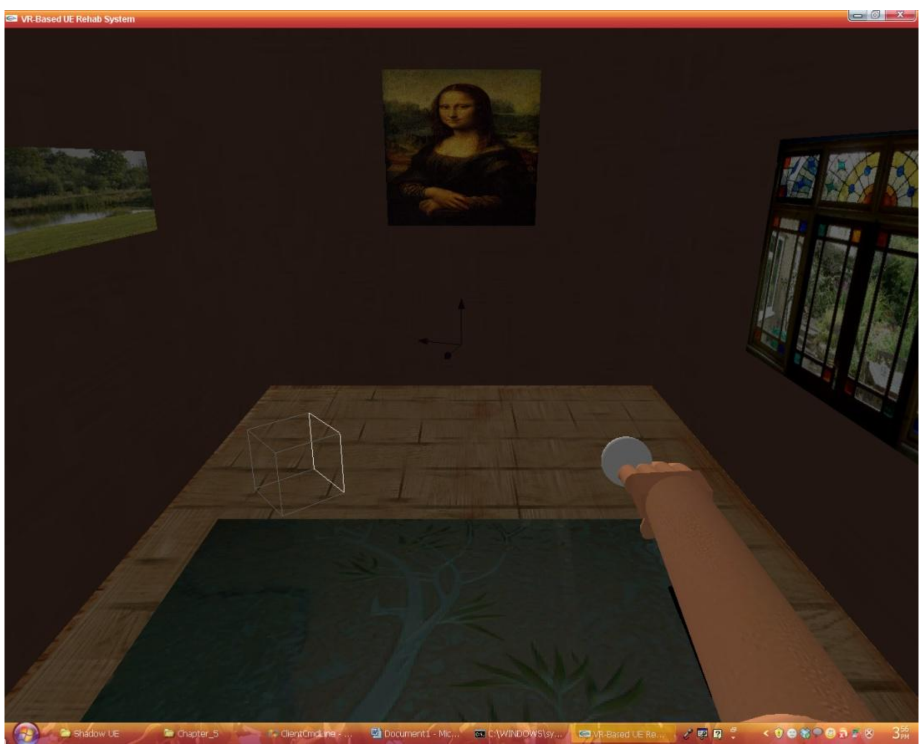

Figure 6.34: **Virtual rendering of the real time horizontal pick and place task**

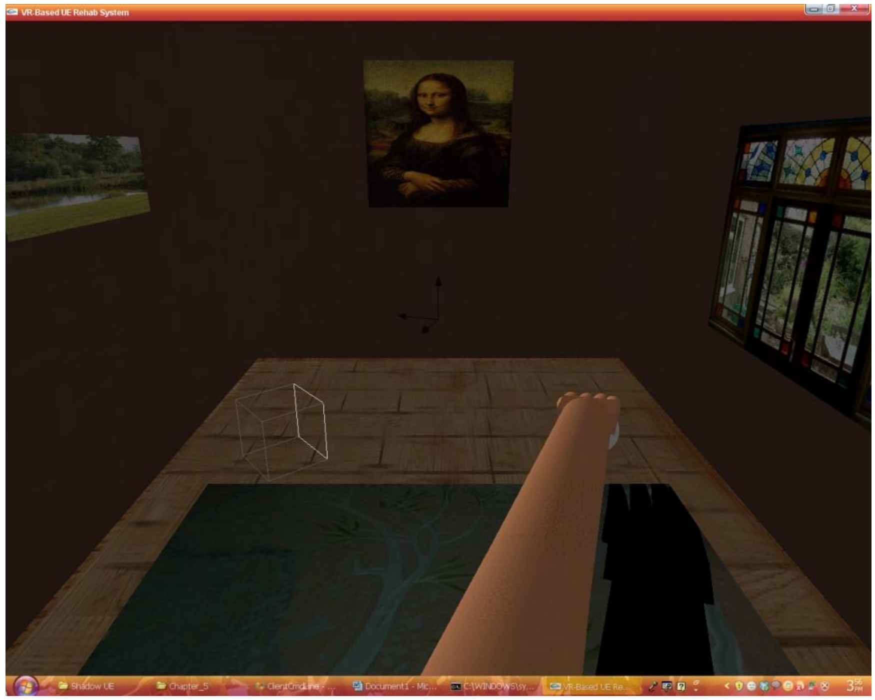

Figure 6.35: **The middle of the distance and the outline of the trajectory followed by the subject during horizontal reaching task**

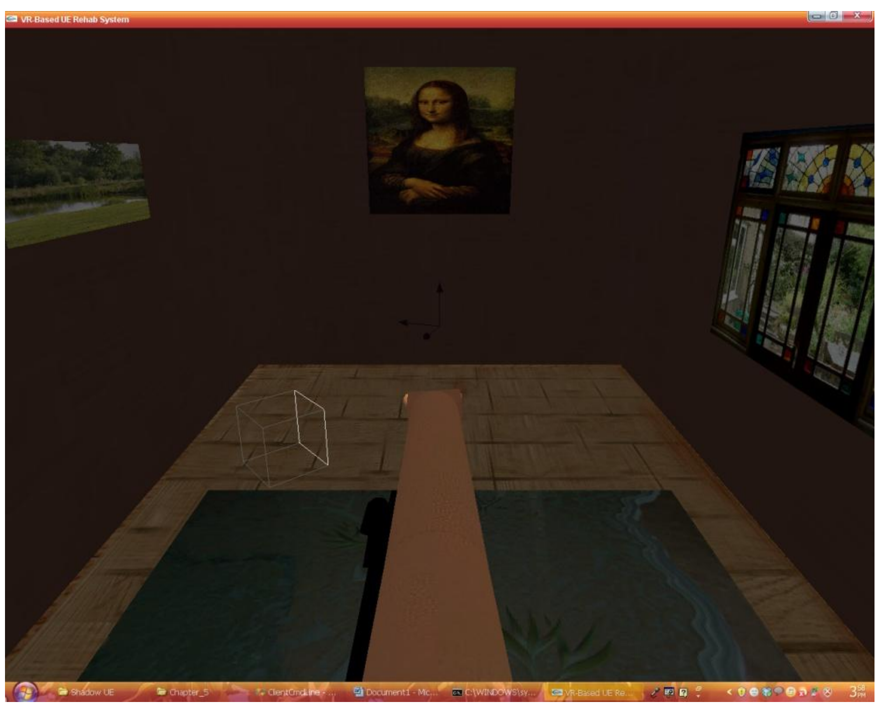

Figure 6.36: Virtual reconstruction of the real time execution of the horizontal pick and place task

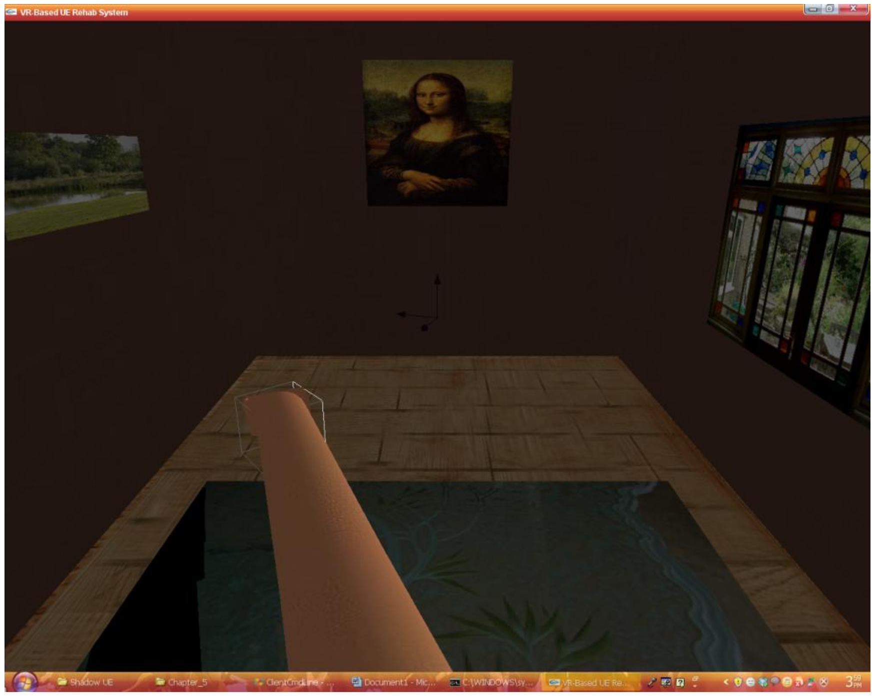

Figure 6.37: **Final Movement in the Saggital plane during the vertical reach movement exercise**

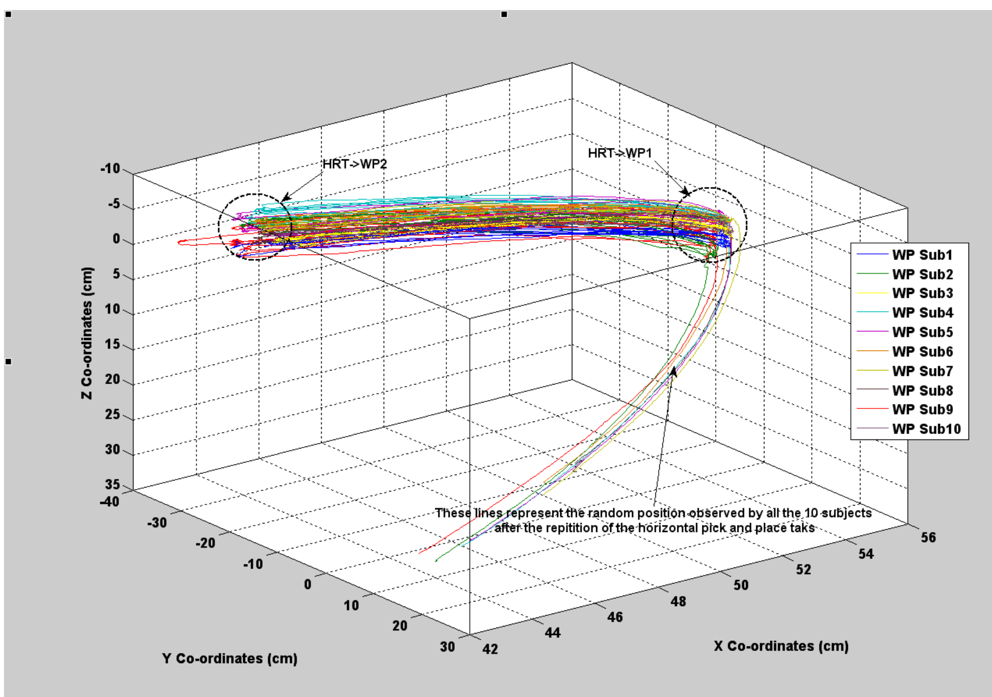

Figure 6.38: **Wrist Trajectory obtained during the horizontal pick and place task**

During the execution of the horizontal pick and place task the volunteers were asked to hold the hand as straight as possible. A Euclidean distance calculated from the origin which was situated on the shoulder of the subject indicates that the mean distances during the task repetition by the subjects are 54.67 cms. There is a linear correlation between the subjects performing the task with precise movement control by following the virtual objects located in the virtual environment. This also shows the virtual trajectories give a more robust precision as the location of the upper extremity could be adjusted according to the avatar which displays the real time motion of the upper extremity in the real world.

There is little movement in the z-direction which is the vertical direction hence, only x and y coordinates are displayed in Figure 6.39.

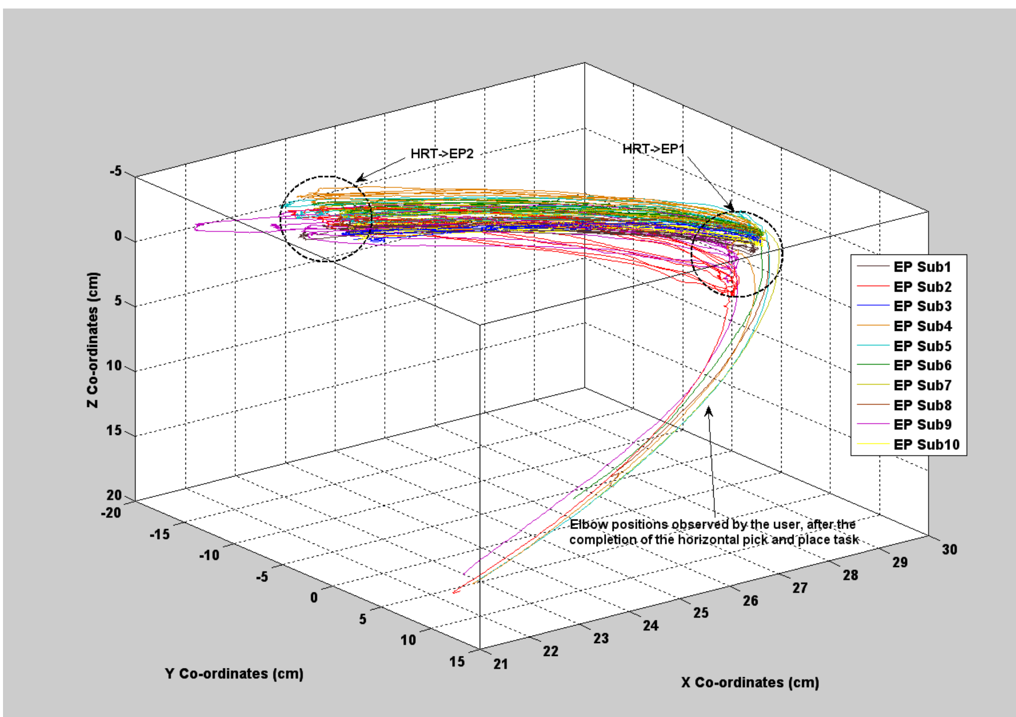

Figure 6.39: **Elbow Trajectory obtained during the horizontal pick and place task**

The mean Euclidean distance from the origin for the subjects and the standard deviations are given in Table 6.13 below

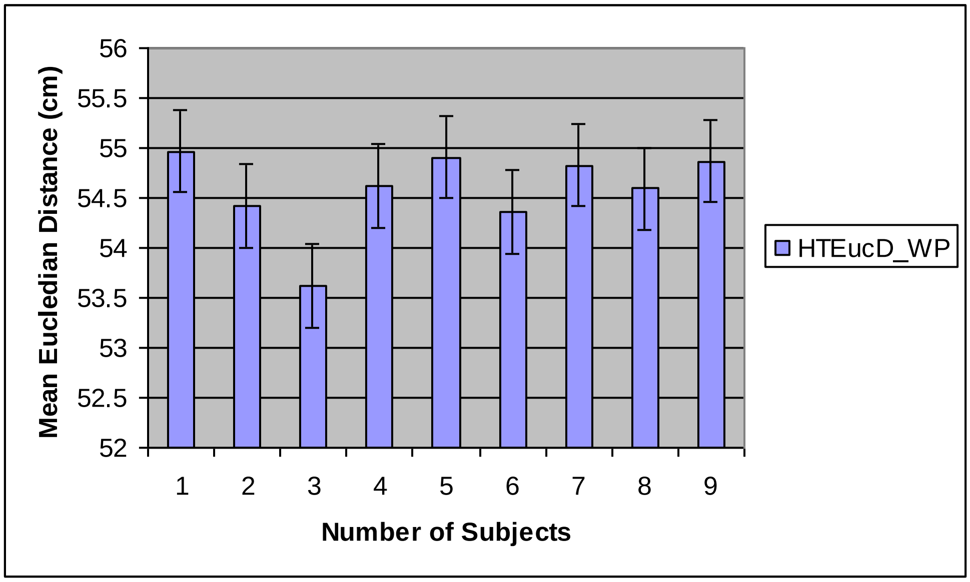

Table 6-13: Mean Euclidean Distance with their standard Deviations

.

It can be seen from the Table 6.13, that there is no significant difference between subjects during the execution of the horizontal pick and place task. This could be either because of the fixed trajectory which the volunteers had to follow during the repetitions they performed. Also, the virtual guide where the users could relate their movement as closely as possible would have motivated them for removing any abnormality in the trajectories over the 5 repetitions

6.8 System Usability Questionnaires

The subjects were asked to fill self report questionnaires adopted from the IBM Computer Usability Test and NASA TLX (Task Load Index) (Appendix –II) (Nasa TLX 2012). The IBM Computer usability test was evaluated on a scale 1-7, with the lower end being the point of strong agreement with the question and the higher end being the point of strong disagreement. The NASA TLX was also evaluated on a scale of 1-7 where the lower bound being the point of very low demand in terms of physical and mental demand where as the very high bound meant that the task required very high demand in terms of the physical and mental involvement. The box plot below Figure 6.40 shows their responses according to their experience interacting with the virtual rehabilitation system. The questions were graded on a scale of 7. These questions tell us the aspects of the system that the user is particularly concerned with and the features or aspects that satisfy the user while performing the tasks.

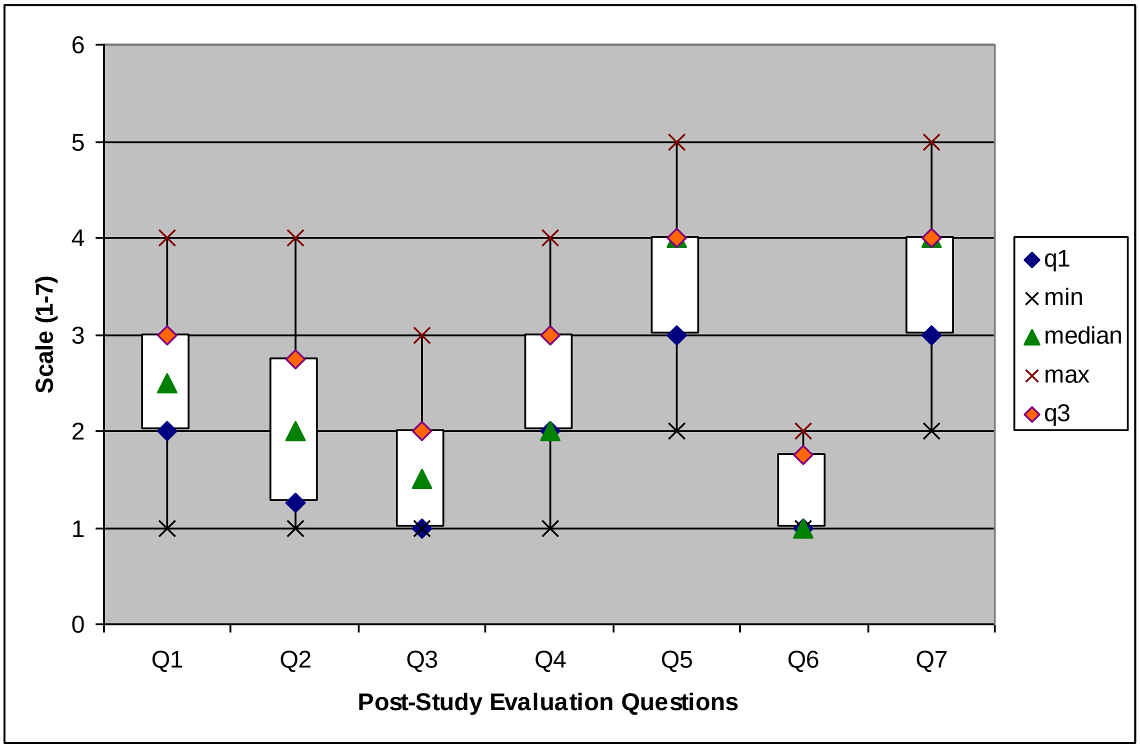

Figure 6.40: System Usability Evaluation

From the box plot it could be observed that over all satisfaction of the system use has been strongly agreed by the sample population (Q1). The VR-based system as reported by the users was simple to use (Q2) Also most of the users were able to complete the VR tasks effectively (Q3). Most of the volunteers agreed that it was easy to learn to use the VR-based system under trial (Q4). The user's feedback on the engagement on the task was strongly favourable but more interactive game like scenarios were some of the useful comments (Q5). Most importantly the tasks were not so very demanding mentally and most of them could execute the tasks without any mental exhaustion (Q6).As reported by the users the tasks were very physically demanding as they had to undergo a series of repetition under one sitting due to time constrain. Also the splint wearing and again executing the drink task could have affected their opinion on the physical side of the system trial. This was done due to the time constrain. The system did introduce fatigue and all these causes would have evolved in to them forming the opinion on the physical side of the system trial (Q7).

6.9 Conclusion

This chapter concluded the full scale integration of the software hardware interface and the development of the rehabilitation exercise. There were three exercise developed solely for the training of the movements which are commonly required for executing the activities of daily living. A calibration exercise has been developed which could be carried out either completely in the virtual environment or with the help of a real world scenario with real world objects and real time virtual mapping. The exercises conducted with the help of the virtual guides in this chapter, where the users upper extremity is mapped onto the virtual scene and interacts with it in real time guides them to accomplish the tasks in had very efficiently. Hence, there are fewer deviations from the trajectories followed over the length of time. A 30 to 45 minutes session was required to complete the three exercises. Though these exercises could either be made more intensive or less depending on the type of treatment required as prescribed by clinicians and therapists. As outlined in the trajectories obtained from the four point calibration task, there were deviations observed in the 5 repetitions of the same task. These deviations (+/- 2 cms) resulted from fatigue as reported but could be minimised through a correction algorithm in the future. So the factor which has made the results somewhat significantly different is fatigue which is developed over time and could be taken into consideration when analyzing he results. A 7 point scale for evaluating the system has been adopted from IBM Computer Usability Test and NASA TLX (Task Load Index) (Appendix –II) (Nasa TLX 2012). The interactivity of the users with the virtual scene and their feedback has been encouraging and the results show a consistency, reliability and repeatability of the system. Since the tasks were done in one session there was more physical demand on the users, so with more flexibility on time and with user's choice of the type of exercise the results could be more promising. Over all this virtual reality based upper extremity stroke rehabilitation system is a complex and useful contribution in the field of whole arm rehabilitation.

CHAPTER 7. Conclusions

7.1 VR Based Upper Extremity Rehabilitation

VR based stroke rehabilitation for the upper extremity functional motor deficits are expanding its way from the clinical setting using the conventional therapy to the home based rehabilitation systems. As discussed in chapter 3, there are a number of technologies which seemed to have a positive impact on the motor deficits of persons impacted by stroke. There still remain a number of aspects which are not yet understood properly. Some researchers have shown dubious results in showing whether virtual reality approaches are more appropriate solutions to upper extremity stroke rehabilitation than the standard approaches. The characteristics of the virtual reality seem to be in a state of test since it's not clear which of them would be more important in the recovery process after stroke.

To address this we have implemented a whole arm rehabilitation system with different virtual environment settings where the real time manipulation and control of the mapped 3D upper extremity is achieved. These interactions also provide an opportunity for audio, visual feedback to the user and different configurations. The prototype system developed as part of this thesis can be used in home setting. The system as demonstrated in the thesis uses the virtual reality, motion sensors and VR glove for upper extremity post stroke rehabilitation. Three exercises were modeled in the virtual environment for the practice of the VR based rehabilitation training. These simulations of the virtual tasks were designed on the implication of both the physical therapy and the functional rehabilitation methods.

The motions sensors (MTx) from the Xsenes technologies, Netherlands were used to obtain the orientation of the upper extremity and the VR glove from DGTech Italy was used to obtain the finger bend during the execution of the tasks in the virtual environment. The motion and bend data were recorded in real time during the performance of the VR exercises in the virtual environment. Data collected during the rehabilitation tasks were stored in the rehabilitation system database for later processing and analysis. These data could also be available for post processing by a remote therapist similar to a tele-rehabilitation system with a remote therapist providing feedback on the improvement of a rehabilitation task performed by a user. In case of a stroke patient performing the same task in place of the healthy individuals in our case, the remote therapist could analyze and evaluate a patients progress and the VR exercises could be modified to suit the a specific rehabilitation goal.

The upper extremity whole arm rehabilitation prototype presents a novel approach to rehabilitation. Healthy subjects could interact with the motion sensors and the VR glove to exercise their upper extremity. The speed and length of the exercise could be controlled by the healthy subject. The sensors could be worn on following a simple guideline from an expert at one time and then it could be followed by any relative or by the user itself if they have either of their arms in normal condition. The user or the carer is required to have an optimum computer literacy of switching on/off the computer and opening and closing a window from a specified location in the PC. The basic guidelines could be available which the carer or the users could follow to perform the rehabilitation exercises effectively though a formal lesson would need to be provided by the expert. At this point only two sensors are needed to carry on the exercise effectively but with added complexity of the system focussing the trunk movements and other compensatory movements, a third sensor could be added which would increase the price of the system by around 1000 pounds.

Data collected during the execution of the VR tasks, suggested that the subjects enjoyed the interaction with the virtual environment as they performed the motion of the upper extremity in real time. Feedback from the Avatar (virtual model of the subject's upper extremity) made the subjects adjust their upper extremity in the real world. The Avatar also acted as a virtual teacher to locate the upper extremity according to the requirement of a specific rehabilitation task. The orientation data collected during the execution of the three standard tasks (common for all ten Healthy Subjects) provided sufficient evidence in support of the system performance. The accuracy and repeatability of the system without minimal drift (+/- 2) were noticeable.

The presence of magnetic materials produced some noise during the rehabilitation tasks which were profoundly outlined in the trajectories obtained after the completion of each tasks. To minimise the effect of magnetic materials a safe circumference of 2 meter radius has been chosen. Since the aim of the system is to provide home based rehabilitation the future work could minimise the interference of magnetic objects by altering the magnetometer output. Also, the user could be notified for possible disturbance in the sensor output while using the sensors close to any magnetic objects. Fatigue was reported by some of the users during the VR exercise sessions, though sufficient rest was provided.

7.2 Participant perceptions

The other aim of the development and testing of the virtual reality based upper extremity stroke rehabilitation system was to provide an insight in the participant perspectives. The ideas from the user perspective were to be welcomed with healthy and elaborate discussions in order to develop guidelines to improve the system. This was achieved by the self report questionnaires provided to the participants after the completion of the training session. The questionnaires targeted the sample of healthy volunteer's in order to extract their views on the effectiveness, acceptability and usability of the VR based upper extremity stroke rehabilitation system.

7.2.1 Additional Scope

In addition to the prepared questionnaires on the usability evaluation procedure, the study could have recorded the comments during the training sessions. This would have enhanced the drawing of a more coherent and better understanding of the users understanding of their physical aspects, psychological aspects, research interaction, involvement during the training session and feedback from the system along with the enjoyment aspects. Other than the recording of the session a structured interview of the users could have been a pertinent tool for better understanding of the underlying scope of improvement of the VR system.

It could be argued that the participants had a stake in laying down a window for improving the system based on their hand on acquaintance of the system, but at the same time end users such as the therapists, rehabilitation managers, consultants and budget holders could also have been involved in the process of providing their opinion and feedback on the system performance. These could well be an integral part of the future works research.

7.3 Thesis Research Contributions

- Development of a Virtual reality based whole arm Stroke rehabilitation system
- Portable, home based and low cost (around 2725 pounds approx) solution to upper extremity stroke rehabilitation
- Prototype testing on 10 healthy volunteers and 10 stroke simulated subjects
- Data analysis and validation of the system for future clinical trials

7.4 Limitations of the study

Alongside the annotation of the research and the feasibility study, the limitations of the research had to be acknowledged. The limitations of the study were addressed during the system design and evaluation in as much detail as possible. Some of the limitations were made part of the future work. One of the basic limitations were the time constrain upon the testing of the system on stroke patients. The other limitation was upon the system calibration which could be independent of the direction the user is facing and the changes in direction during the training task. This limitation could be addressed in the future work where a facing correction could be performed before the testing of the system on healthy volunteers or stroke patients.

Apart from using a 2D reference for measuring the accuracy of the orientation from the motion sensors, the VICON system (Vicon 2011) would have provided a better option for comparing the results from the sensors.

The present version of the whole arm rehabilitation system could not measure the trunk compensation, while the reaching activity. Also, the users were asked to sit straight without any trunk or hip motion to restrict the shoulder as a fixed point. Stroke subjects show the tendency of moving their trunk while reaching tasks, such as pick and place, reach and grasp. Since the shoulder or trunk sensor were not incorporated in the present design the shoulder were presented as fixed origin. The third sensor for measuring these compensatory movements has been included in the future work.

7.5 Future Research Directions

Better rehabilitation outcome focused exercises for fine motor skills for both the upper extremity and the fingers need to be designed and tested The left arm model needs to be designed to allow the users to perform the rehabilitation training with either of the affected upper extremity with ease. The testing of the system on stroke subjects and a complete analysis of the system with the therapists could be aimed at. A complete set of exercise databases on the clinical guidelines have to be designed and developed to provide more flexibility on the choice during rehabilitation training. The exercises could be made specific to the stroke subjects in order to follow a treatment plan laid by the clinicians for better outcomes.

The VR glove could be modified to provide more resistance to the users in order to train their finer strength during the rehabilitation exercise. More interactive game-like exercises which could serve to hold the motivation level of the user to extended period of time in order to perform more repetitions.

The whole arm rehabilitation system would incorporate a sensor at the shoulder which would measure the trunk compensation and that would be included in the kinematics of the upper extremity. The shoulder would not be fixed and the upper limb hierarchy would have the base of the trunk as the origin. The whole arm rehabilitation system is given in Figure 7.1, where the W_S s the motion sensors located at the wrist, E_S is the sensor located at the upper arm and the S_S sensor is the sensor located at the shoulder for the trunk compensation during adaptive movement in case of stroke subjects. All the three sensors are connected to the Xbus master, which is connected to the PC through serial port RS323. The VR glove is worn by the user for finger flexion extension during the grasp and manipulation of objects in the virtual scene. The virtual simulation of a real world scenario is running on a windows PC.

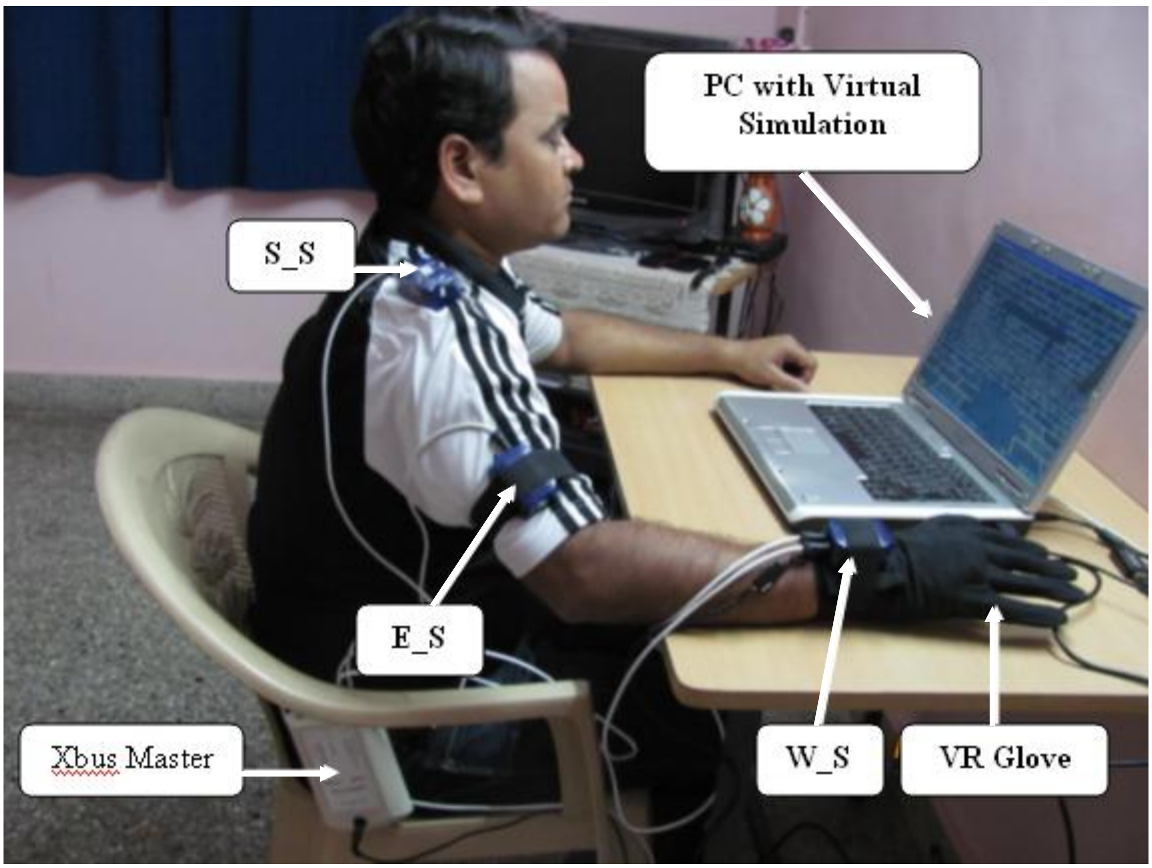

Figure 7.1Whole Arm Rehabilitation Prototype with the shoulder sensors for Trunk Compensation

The present system is aimed at providing rehabilitation to the right arm only. This could well be modified to suit both the arms simultaneously. The VR glove is also for the right hand. At the later stage, the system could be integrated for both the right and left hand for more interactivity during the training exercise with the virtual environment.

REFERENCES

Adams, R. (1990). “Attention Control training and behaviour management,” *Butterworth-Heinemann*, Oxford.

Aisen M. L., Krebs H. I., Mcdowell F., Hogan N., and Volpe B. T. (1997). “The effect of robot assisted therapy and rehabilitative training on motor recovery following stroke,” *Archives of Neurology*, 54:443–446.

Alaqtash M., Sarkodie-Gyan T., Kreinovich V., (2011). "Assessment of Functional Impairment in Human Locomotion: A Fuzzy-Motivated Approach" *Technical Report.*

Anatomical Terminilogy, (2012). Accessed: 29 Feb. 12, http://training.seer.cancer.gov/anatomy/body/terminology.html

Angel E., (2005), “Interactive Computer Graphics: A Top Down Approach Using OpenGL,” *Addison Wesley*. ISBN-10: 032131252X ISBN-13: 978-0321312525.

Angel, E., Shreiner, D., (2011). “Interactive Computer Graphics: A Top-Down Approach with Shader-Based OpenGL, 6/E,” Addison-Wesley. ISBN-10: 0132545233 ISBN-13: 9780132545235.

August K, Bleichenbacher D., Adamovich S (2005).“Virtual reality physical therapy: A Telerehabilitation tool for hand and finger movement exercise monitoring and motor skills analysis,” *Proceedings of the IEEE 31st Annual Northeast Bioengineering Conference*: 73-74.

Badler, N. I. (1999). "Animation control for real-time virtual humans." *In Communications of the ACM*: 64-73.

Badler, N. (1992). "Graphical behavior and animated agents." *In Advanced Techniques in Human Modeling, Animation, and Rendering* (Course Notes No. 17). ACM SIGGRAPH

Badler, N., Smoliar, S. (1979). "Digital representations of human movement." *ACM Computer Survey*, vol 11

Bardorfer, A., Munih, M., and Zupan, A. (2001). "Upper limb motion analysis using haptic interface," *IEEE/ASME Transactions on Mechatronics*, 6(3):253–260.

Baheux K, Yoshizawa M, Seki K, Handa Y (2006). "Virtual reality pencil and paper tests for neglect: a protocol," *Cyberpsychol Behav*, 9(2):192-195.

Beer RF, Dewald JPA, Dawson ML, Rymer WZ.(2004), "Target-dependent differences between free and constrained arm movements in chronic hemiparesis,". *Exp Brain Res*, 156(4):458–70.

Bobath, B., (1990). "Adult Hemiplegia: Evaluation and Treatment*," Heinemann Medical Books,* Oxford, pp. IX-19

Boian, R., Sharma, A., Han, C., Merians, A. S., Burdea, G., Adamovich, S., Recce, M.,Tremaine, M., & Poizner, H. (2002). "Virtual Reality-Based Post Stroke Rehabilitation," *Proceedings of Medicine Meets Virtual Reality*,64-70,

Bonato P., (2003). "Wearable Sensors/Systems and Their Impact on Biomedical Engineering," *IEEE Engineering in Medicine and Biology Magazine*, 22(3):18–20.

Bosecker C, Dipietro L, Volpe B and Krebs, H I. (2010). "Kinematic Robot-Based Evaluation Scales and Clinical Counterparts to Measure Upper Limb Motor Performance in Patients With Chronic Stroke." *Neurorehabil Neural Repair* 24:62-69 DOI:10.1177/1545968309343214

Bouten, C. V. C., Koekkoek, K. T. M., Verduim, M., Kodde, R., Janssen, J. D. (1997). "A triaxial accelerometer and portable processing unit for the assessment daily physical activity," *IEEE Trans. Biomed*. 44: 136-147

Bowman, D. A., E. Kruijff, J. J. LaViola and I. Poupyrev (2001). "An Introduction to 3-D User Interface Design," *Presence* 10(1): 96 -108

Broeren, J., A. Bjorkdahl, R. Pascher and M. Rydmark (2002). "Virtual reality and haptics as an assessment device in the postacute phase after stroke," *Cyberpsychol Behav* 5(3): 207-11.

Broeren, J., M. Dixon, K. Stibrant Sunnerhagen and M. Rydmark (2006). "Rehabilitation after stroke using virtual reality, haptics (force feedback) and telemedicine," *Stud Health Technol Inform* 124: 51-6.

Brooks, B., J. McNeil, et al. (1999). "Route learning ins a case of amnesia: A preliminary investigation into the efficacy of training in a virtual environment." *Neuropsychological Rehabilitation* 9: 63-76.

Bruno-Petrina, Accessed 13/01/2012, *http://emedicine.medscape.com/article/324386-overview*

Bryanton C., Bosse J., Brien M., McLean J., McCormick A., Sveistrup H.,(2006). "Feasibility, motivation, and selective motor control: virtual reality compared to conventional home exercise in children with cerebral palsy," *Cyberpsychology & Behaviour*. 9, 123-8.

Burdea, G. & Coiffet P. (2003). Virtual Reality Technology, Wiley-IEEE Press

Burdea, G. & Coiffet P. (2003). Virtual Reality Technology, Wiley-IEEE Press.

Burgar, C.G., Lum, P.S., Shor, P.C., Van der Loos, H.F.M. (Jan 9 2001), "Development of robots for rehabilitation therapy: The Palo Alto VA/Stanford experience," (VA Research and Development), Available: *http://www.vard.org/jour/00/37/6/burga376.htm (Accessed: 14/10/09)*.

Butefisch C, Hummelsheim H., Mauritz K-H (1995). "Repetitive training of isolated movements improves the outcome of motor rehabilitation of the centrally paretic hand." *J Neurol Sci* 130: 59-68

Butefisch C, Hummelsheim H., Mauritz K-H (1995)."Repetitive training of isolated movements improves the outcome of motor rehabilitation of the centrally paretic hand," *J Neurol Sci* 130: 59-68.

Burdea G. "Keynote Address: Virtual Rehabilitation-Benefits and Challenges," 1st International Workshop on Virtual Reality Rehabilitation (*Mental Health, Neurological, Physical, Vocational*) VRMHR 2002 Lausanne, Switzerland, November 7 and 8, pp. 1-11, 2002.

Buxton, W., & Fitzmaurice, G.W. (1998). HMD's, Caves, & Chameleon: A human-centric analysis of interaction in virtual space. . p. 64-68.

Cameirao, M.S., Bermudez i Badia, S. et al. (2008). "Virtual reality based upper extremity rehabilitation following stroke: a review." *Journal of CyberTherapy & Rehabilitation* 1(1), 63-74.

Capek, K. (1921). *Retrieved 14/10/09, 2009, from http://www.karelcapek.net/rur.htm*.

Caplan, L. R. (2006). “Stroke,” American Academy of Neurology Press quality of life guides. New York : Saint Paul, MN : Demos ; AAN Press, *American Academy of Neurology*

Caplan L.R.,Bogousslavsky J.,(2008),"Uncommon causes of Stroke,"Cambridge University Press.

Caplan, L. R. (2006). Stroke. American Academy of Neurology Press quality of life guides New York : Saint Paul, MN : Demos ; AAN Press, American Academy of Neurology,

Carr J, Shephred R. (2006). “Stroke Rehabilitation Guidelines for Exercise and training to Optimize Motor Skill,” *ButterWorth Heinemann*.

Cerullo, L.J., (1986). “Stroke Rehabilitation,” *Butterworth Publishing*, Stoneham, MA, 1986.

Chao, E. Y. & K. N. An. (1978). "Graphical interpretation of the solution to the redundant problem in biomechanics." *Journal of Biomechanical Engineering*. 100: 159-167.

Chen Yu-Ping, Kang Lin-Ju, Chuang Tien-Yow, Doong Ji-Liang, Lee Shwn-Jan, Tsai Mei-Wun, Jeng Suh-Fang, Sung Wen-Hsu. (2007). “Use of Virtual Reality to Improve Upper-Extremity Control in Children With Cerebral Palsy: A Single-Subject Design,” *Physical Therapy*,87(11):1441-1457

Chortis, A., Standen, P.J., Walker, M. (2008)." Virtual reality system for upper extremity rehabilitation of chronic stroke patients living in the community." *Proc. 7th ICDVRAT with ArtAbilitation, Maia, Portugal, ICDVRAT/University of Reading, UK*; ISBN 07 049 15 00 6, pp.221-228

Clark, R. A., Bryant, A. L. et al (2010). "Validity and reliability of the Nintendo Wii Balance Board for assessment of standing balance," *Gait Posture*, 31 (3), 307-310.

Conner D. A. Harvey (2002). "Errorless learning using haptic guidance: research in cognitive rehabilitation following stroke," *Proc. 4th Intl Conf. Disability*, Virtual Reality & Assoc. Tech., Veszprém, Hungary, University of Read ing, UK.

Coote S, Murphy B., Harwin W, Stokes E (2008). "The effect of the GENTLE/s robot-mediated therapy system on arm function after stroke," *Clinical Rehabilitation* 22: 395-405

Crosbie, J.H., McDonough, S. M., Lennon, S., Pokluda, L. and McNeill, M. D. J. (2004) "Virtual Reality in the Rehabilitation of the Upper Limb After Stroke: the User's Perspective," *In Proceedings of the 5th International Conference on Disability, Virtual Reality & Associated. Technologies*, Oxford

Cruz-Neira C, S. D., DeFanti TA, Kenyon RV, Hart JC (1992). "The CAVE automatic virtual environment," *Communications* 38: 64-72

Cuber Glove, (2009). Accessed : 29 Feb. 12, http://www.cyberglovesystems.com/sites/default/files/CyberGloveII_Brochure_2009.pdf

Davies RC, Lofgren E, Wallergard M, Linden A, Boschain K, Minor U, Sonesson B, Johansson G.(2002). "Three applications of virtual reality for brain injury rehabilitation of daily tasks," *Proceedings of the 4th International Conference on Disability, Virtual Reality and Associated Technology*. Vresprem, Hungary: University of Reading (United Kingdom). 93–100

Dean C, Mackey. F. (1992). "Motor assessment scale scores as a measure of rehabilitation outcome following stroke," *Aust J Physiother* 38: 31-35

Doscher, J. (2007). Accelerometer Design and Applications. Analog Devices. URL: ttp://www.analog.com/Analog_Robot/static/library/techArticles/mems/sensor$971.$pdf

Dvir Z (1978) "Biomechanics of the shoulder joint." *PhD Thesis,University of Strathclyde, Glasgow*.

Eglowstein, H.,(1990). “Reach out and touch your data,” *Byte*, 15(7):283–290

Ellis S.R. (1991), “Nature and origins of virtual environments: A bibliographic Essay ,” *Computer Systems in Engineering*. Vol.2, No.4, pp.321-347.

Ellis MD, Sukal T, Demott T, Dewald JPA.(2008), "Augmenting clinical evaluation of hemiparetic arm movement with a laboratory-based quantitative measurement of kinematics as a function of limb loading,". *Neurorehabil Neural Repair*.

Ehrsson HH, Fagergren A, Jonsson T, Westling G Johansson RS, Forssberg H. (2000), "Cortical activity in precision versus power grip tasks: an fMRI study,". *Journal of Neurophysiology*; 83: 528-536

Emmerich, H.; Schofthaler, M. (2000). "Magnetic field measurements with a novel surface micromachined magnetic-field sensor." *IEEE Trans. Electron Devices*. 47:972–977.

Eng, Y.-C. W., Chin-Hao; Wu, Fang-Jing; Huang, Chi-Fu; King, Chung-Ta; Lin, Chun-Yu; Sheu, Jang-Ping; Chen, Chun-Yu; Lo, Chi-Yuan; Yang, Chien-Wen; Deng, Chi-Wen (2009). “A wireless human motion capturing system for home rehabilitation,” *Proceedings 10th International Conference on Mobile Data Management: Systems,* Services and Middleware. 359-360.

DGTech VHand, (2007). Accessed: 29 Feb. 12, http://www.dg-tech.it/vhand/eng/

Duncan PW, Goldstein L., Horner RD (1994). “Similar motor recovery of upper and lower extremities after stroke,” *Stroke* 25: 1181-1188.

Ferraris, F., Grimalde, U., Parvis, M. (1995). “Procedure for effortless in-field calibration of three axis rate gyros and accelerometers,” *Sens. Mater* **7**(5): 311.

Feys H. M., De Weerdt W. J., Selz B. E., Steck G. A. C., Spichiger R., Vereeck L. E., Putman K. D., Van Hoydonck G. A. ,(1998)," Effect of a Therapeutic Intervention for the Hemiplegic Upper Limb in the Acute Phase After Stroke : A Single-Blind, Randomized, Controlled Multicenter Trial," *Stroke* 1998, 29:785-792

Finley MA, Dipietro L, Ohlhoff J, Whitall J, Krebs H I, Bever CT (2009). “The effect of repeated measurements using an upper extremity robot on healthy adults,” *Journal of Applied Biomechanics* 25(2):103-110.

Foulkes MA, Wolf PA, Price TR, Mohr JP, Hier DB (1988). "The Stroke Data Bank: design, methods, and baseline characteristics," *Stroke* 19:547–554

Fugl-Meyer AR, J. L., Leyman I, Olsson S, Steglind S. (1975). "The poststroke hemiplegic patient. 1. A method for evaluation of physical performance," *Scand J Rehabil Med* **7**: 13-31.

Garcia JH, Liu KF, Yoshida Y, Lian J, Chen S, del Zoppo GJ (1994) Influx of leukocytes and platelets in an evolving brain infarct (Wistarrat). Am J Pathol 144:188 –199.

Gardner, D. L., (1989). "The Power Glove," *Des. News*, 45:63–68

Garu, O. (2003). "Virtual Art-From Illusion to Immersion," *MIT Press*, ISBN-10: 0-262-07241-6.

Gehringer, D., Walsh, A.E. (2002). "Java 3D: API Jump-Start," *Prentice Hall PTR*, Upper Saddle River, NJ.

Gotsis, M. (2009). "Games, virtual reality, and the pursuit of happiness," *IEEE Computer Graphics and Applications*. 29(5) 14-19.

Gourlay D, Lun KC, Lee YN, Tay J.(2000). "Virtual reality for relearning daily living skills," *Int J Med Inform*.60: 255–61

Gowland, C. (1982). "Recovery of Motor Function Following Stroke: Profile and predictors," *Physiother Can* 34: 77-84.

Grealy, M. A., Johnson, D. A., & Rushton, S. K. (1999). "Improving cognitive function after brain injury: The use of exercise and virtual reality," *Archives in Physical Medicine and Rehabilitation* 80 661-667.

Green, J. Krakauer, D. (2008). New iMEMS Angular-Rate-Sensing Gyroscope. *ADI Micromachined Products Division*.

Greenleaf WJ, T. M. (1994). "Augmenting reality in rehabilitation medicine," *Artif Intell Med* 6: 289-299.

Gudukbay, U., Ozguc, B., Memisoglu, A., Yesil, M. S. (2008). " Modeling, Animation, and Rendering of Human Figures.

Gyroscope, (2012), Acessed: 29 Feb. 12http://hyperphysics.phy-astr.gsu.edu/hbase/gyr.html

Hafer-Macko CE, Ryan AS, Ivey FM, Macko RF. (2008), "Skeletal muscle changes after hemiparetic stroke and potential beneficial effects of exercise intervention strategies,".*J Rehabil Res Dev*, 45(2):261–272.

Hand and Micro Sugery, (2012). Accessed 29 Feb 2012. http://www.cmki.org/images/HWAS2.gif)

Harris,J.E.,Eng,J.J.(2007), "Paretic Upper-Limb Strength Best Explains Arm Activity in People With Stroke," *Journal of the American Physical Therapy Association*,Vol 87 (1),pp.88-97

Harrison, A., Derwent, G., Enticknap, A., Rose, F.D. and Attree, E.E. (2002). “The Role of Virtual Reality Technology in the Assessment and Training of Inexperienced Powered Wheelchair Users,” *Disability and Rehabilitation*, 24(11-12):599-606.

Haurwitz, B. (1966). "Coriolis and the deflective force. *Bull. Amer. Meteor. Soc*., 47, 659.

Harwin W. S., Patton J. L. and Edgerton V. R., (2006). “Challenges and Opportunities for Robot-Mediated Neurorehabilitation,” *Proceedings of the IEEE*, 94(9):1717-1726.

Heilig, M. L. (1962).“Sensorama Simulator,“ *U. S. Patients*. US

Hendricks, H. T., J. van Limbeek, et al. (2002). "Motor recovery after stroke: a systematic review of the literature." *Arch Phys Med Rehabil* 83(11): 1629-37.

Hill, F. S., Kelley, S. M. (2007). "Computer Graphics Using OpenGL-third edition." *Prentice Hall, Computer Science*, ISBN 0-13-149670-0

Hofmann ,F.; Henz J.,(1995). “The TU-Berlin SensorGlove,” *Tech. Univ. Berlin*, Berlin, Germany, Tech. Rep.

Hofmann, F., (1998).“Der TU-Berlin Sensorhandschuh, technische Beschreibung und aktueller Stand,” *Tech. Univ. Berlin*, Berlin, Germany, Tech. Rep.

Hogan, N., Krebs H. I., Charnnarong J., Srikrishna P., and Sharon A., (1992). “MITMANUS: Aworkstation for manual therapy and training,” *In Proc. IEEE Int. Workshop Robot Hum. Commun*., 161–165.

Hogfors, C., Sigholm, G., Herberts, P., (1987). "Biomechanical model of the human shoulder - I." *Elements. Journal of Biomechanics* 20:157-166.

Holden, M.K., Dyar, T.A., Schwamm, L. and Bizzi, E. (2005). "Virtual-Environment-Based Telerehabilitation in Patients with Stroke. Presence: Teleoperators & Virtual Environments," 14(2): 214-233.

Holden M K, Dyar T A, Dayan-Cimadoro L (2007). "Telerehabilitation using a virtual environment improves upper extremity function in patients with stroke," *IEEE Trans Neurl Syst Rehabil Eng*.15(1):36-42.

Housman S.J., Le V., Rahman T., Sanchez Jr R.J., Reinkensmeyer D.J., (2007)."Arm-Training with T-WREX After Chronic Stroke: Preliminary Results of a Randomized Controlled Trial," *IEEE 10th International Conference on Rehabilitation Robotics***.** 562-568.

H.R., E.(1995). Introduction To Robotics Mechanics and Control. Pearson, Prentice Hall, thrid Edition.

Hubschmann, S., Schneider, M. (1996). Magnetoresistive Sensors Principles of Operation and Applications. *IETREX*

Intercollegiate Stroke Working Party. (2008). "National Clinical Guidelines for Stroke (3rd Edition)," *London:Royal College of Physicians*.

Jack, D., Boian, R., Merians, A. S., Tremaine, M., Burdea, G. C., Adamovich, S. V., Recce, M. & Poizner, H. (2001). "Virtual Reality-Enhanced Stroke Rehabilitation," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 9(3):308-318,

Jang S. H, You S. H., Hallett M., Cho Y. W., Park C. M., Cho S. H., Lee H. Y. , Kim T. H. (2005). "Cortical reorganization and associated functional motor recovery after virtual reality in patients with chronic stroke: an experimenter-blind preliminary study," *Archives of Physical Medicine and Rehabilitation*, 86(11):2218-2223.

Jazar, Reza N., (2007). Theory of Applied Robotics: Kinematics, Dynamics and Control,Springer, New York.

Johnstone, M. (1976). "The Stroke Patient:Principles of Rehabilitation," *Churchill Livingstone*, Edinburgh London and New York.

Kalawsky, R. S. (1993). “The science of virtual reality and virtual environments : a technical, scientific and engineering reference on virtual environments,” *Addison-Wesley*, Wokingham, England ; Reading, Mass

Kalman, R., E. (1960). "A new Approach to Linear Filtering and Prediction Problems", *Transactions of the ASME–Journal of Basic Engineering*, 82 (Series D): 35-45. Copyright © 1960 by ASME

Kalman, R.E., Bucy R.S. (1961)."New results in Linear Filtering and Prediction Theory, *Journal of Basic Engineering*, 83:95-108

Kapandji, I.A., 1980. Physiologie articulaire. 1. Membre supérieur. Maloine, 5è édition, Paris.

Karlsson, N. Karlsson, B. Wide, P., (1998). “A glove equipped with finger flexion sensors as a command generator used in fuzzy control system,” *IEEE Trans. Instrum. Meas*., 47(5):1330–1334

Kemp, B., Janssen, A. J. M. W., and vAN Der Kamp, B. (1998). “Body position can be monitored in 3d using miniature accelerometers and earth-magnetic field sensors,” *Electro-encephalogr. Clin. Neuro-physiol./Electromyogr. Motor Control*, 109: 484 488

Keshner, E. (2004). Virtual reality and physical rehabilitation: A new toy or a new research and rehabilitation tool? *Journal of NeuroEngineering and Rehabilitation*, 1(1), 8.

Kim J., Kim K., Kim D. Y., Chang W. H., Park C. I., Ohn S. H., Han K., Ku J., Nam S. W, Kim I. Y. and Kim S. I. (2007). “Virtual environment training system for rehabilitation of stroke patients with unilateral neglect: crossing the virtual street,” *Cyberpsychol Behav*, 10(1):7-15.

Kim K., Kim J., Ku J., Kim D. Y., Chang W. H., Shin D. I., Lee J. H., Kim I. Y., Kim S. I. (2004). “A virtual reality assessment and training system for unilateral neglect,” *Cyberpsychol Behav*, 7(6):742-749.

Kizony R., Katz N., Weiss P.L. (2003). “Adapting an immersive virtual reality system for rehabilitation,” *J Visual Comput Anim*.;14:261–68.

Kizony, R., Katz, N. and Weiss, P. (2004). “Virtual Reality Based Intervention in Rehabilitation: Relationship between Motor and Cognitive Abilities and Performance within Virtual Environments for Patients with Stroke,” *In Proceedings of the 5th International Conference on Disability, Virtual Reality and Associated Technologies*, 19-25.

Krebs, H.I., Hogan, N., Aisen, M.L., & Volpe, B.T. (1998). “Robot-aided neurorehabilitation,” *IEEE Transactions on Rehabilitation Engineering*, 6(1): 75-87.

Krakauer, J.W., (2006), “Motor learning: its relevance to stroke recovery and Neurorehabilitation,”. *Curr Opin Neurol*, 19(1):84–90.

Kuhlen T, D. C. (1995). “Virtual reality for physically disabled people,” *Comput Biol Med* 25: 205-211.

Kurta, S., Makzkawa, M., Kobayashi, H., Takahash,A.,Toku,R.(1999). "Joint motion monitoring by accelerometers set at both near and sides around the joint." *In Proceedings of the 20th Annual International conference of IEEE Engineering in Medicine and Biology Society*.

Kuttuva M, Boian R, Merians A, Burdea G, Bouzit M, Lewis L, Fensterheim D (2006). “The Rutgers Arm, a rehabilitation system in virtual reality: a pilot study,” *Cyberpsychology and Behaviour*, 9(2):148-151.

Kwakkel G, Wagenaar R., Koelman TW (1997).“Effects of intensity of rehabilitation after stroke:a randomised trial,” *Lancet* 354: 191-196.

Kwakkel G, Kollen B, van der Grond J, Prevo AJ. (2003) "Probability of regaining dexterity in the flaccid upper limb,". *Stroke*,34:2181–6.

Kwakkel, G., B. Kollen, et al. (2004). “Understanding the pattern of functional recovery after stroke: facts and theories,” *Restor Neurol Neurosci* 22(3-5): 281-99.

Kwakkel G, Kollen B., Krebs HI (2008). “Effects of robot assisted therapy on upper limb recovery after stroke:a systematic review,” *Neuro Rehabil and Neur Rep* 22: 111-121.

Lance, J. (1980). “Symposium synopsis. In Spasticity:Dsiorder Motor control,” *Year Book*, Chicago

Landau, W. (1980). Spasticity:What is it?What is it not? In Spasticity: Disorder Motor Control, Year Book, Chicago.

Lang C.E., Wagner J.M., Bastian A.J., Hu Q., Edwards D.F., Sahrmann S.A., (2005). "Deficits in grasp versus reach during acute hemiparesis." *Exp Brain Res*. 166: 126-36

Lasseter,J. (1987). "Principles of traditional animation applied to 3D computer animation," *ACM Computer Graphics (Proc. of SIGGRAPH'87*), 21(4):35–44

LaViola, J. J., (1999). "A survey of hand posture and gesture recognition techniques and technology," *Brown Univ., Providence, RI, Tech. Rep*. CS-99-11

Lee D.N., A. E. (1974). "Visual proprioceptive control of standing in human infants," *Percept Psychoanalysis* 15: 529-532.

Leclercq,A.,Akkouche S.,Galin, E.,(2001). "Mixing triangle meshes and implicit surfaces in character animation," in Proceedings of Animation and Simulation, pp. 37–47.

Legget, P. (1997)." Principles of Human Movement in Lloyd P. et al. Eds (1997) The guide to the handling of patients: Introducing a safer Handling Policy." *Fourth edition. NBPA/RCN Teddington Middlesex*

Lewis-Brooks, A. (2004). "Humanics-A Feasibility Study to Create a Home Internet Based Telehealth Product to Supplement Acquired Brain Injury Therapy," *In Proceedings of the 5th International Conference on Disability, Virtual Reality and Associated Technologies,* 11-18.

Li H, Song A. (2009). "Force assistant master-slave telerehabilitation robotic system," Journal of Southeast University 24(1): 42-45.

Liepert J., Miltner W., Bauder H. (1998). "Motor Cortex plasticity during constraint-induced movement therapy in stroke patients," *Neurosci Lett* (250): 5-8.

Lin, K.-C., Cermak, S. A., Kinsbourne, M., & Tro m b l y, C. A. (1996). "Effects of left-sided movements on line bisection in unilateral neglect." *Journal of the International Neuropsychological Society*, 2:401-411.

Lo, A. C., P. D. Guarino, et al. (2010). "Robot-assisted therapy for long-term upper-limb impairment after stroke." N Engl J Med 362(19): 1772-83.

Lotters, J. (1998): “Design, fabrication and characterization of a highly symmetrical capacitive triaxial accelerometer,” *Sensors Actuators A: Phys*., 66: 205-212

Loureiro R., Amirabdollahian F., Topping M., Driessen B., and Harwin W.(2003) “Upper limb robot mediated stroke therapy-GENTLE/s approach,” *Special Issue Rehabil. Robot. J. Auton. Robots*, 15: 35–51.

Lucca, L. F. (2009). "Virtual reality and motor rehabilitation of the upper limb after stroke: a generation of progress?" J Rehabil Med 41(12): 1003-100.

Luinge, H. J. (2002): 'Inertial Sensing of Human Movement'. *PhD thesis, University of Twente*.

Lum PS, Burgar CG, Kenney DE, Van der Loos HFM(2000).“Quantification of force abnormalities during passive and active-assisted upper-limb reaching movements in post stroke hemiparesis,” *IEEE Trans Biomed Eng* 46: 652– 662.

Lum PS, Burgar CG, Kenney DE, Van der Loos HFM. (2002a).“Robot-assisted movement training compared with conventional therapy techniques for the rehabilitation of upper limb motor function following stroke,” *Arch Phys Med Rehab* 83: 952–959.

Lum, P., Reinkensmeyer, D., Mahoney, R., Rymer, W. Z., and Burgar, C. (2002b). “Robotic devices for movement therapy after stroke: current status and challenges to clinical acceptance,” *Top Stroke Rehabil*, 8: 40-53

Lum PS, Burgar CG, Van Der LM, Shor PC, Majmundar M, Yap R. (2005). “The MIME robotic system for upper-limb neuro-rehabilitation: Results from a clinical trial in subacute stroke,” *Proceedings of the 2005 IEEE 9th International Conference on Rehabilitation Robotics*: 511-514.

Lum PS, Burgar CG, Van Der LM, Shor PC, Majmundar M, Yap R (2006). “MIME robotic device for upper-limb neurorehabilitation in subacute stroke subjects: A follow-up study,” *Journal of Rehabilitation Research and Development* 43(5) 631-642.

Lundvik G.A., G. G., Salford E. (1999). “Interaction Between patient and physiotherapist:a qualititive study reflecting the physiotherapist's perspective,” *Physiother Res Int* 4: 89-109.

Luttgens, K., Hamilton, N. (1997). "Kinesiology: Scientific Basis of Human Motion, 9th Ed." *Madison, WI: Brown & Benchmark.*

MacWalter RS, F. H. (2003). “Stroke Explained,” *Altman Publishing*, 7 Ash Copse, Bricket Wood, St Albans, England.

Magill, R. A. (1998). “Motor Learning Concepts and Applications,”*McGraw-Hill*, New York

Magill, R. A. (2001). “Motor Learning Concepts and Applications,” *McGraw-Hill*, New York.

Magnet.Fsu (2008). BibTeX-magnet.fsu, INteractive Hall Effect. [On-line; accesed-March-2012]

Maitra K.K., Junkins M.D., (2004). "Upper extremity movement pattern ofa common drinking task in well elderly women: A pilot study." Occupational Therapy International, 11(2):67-81.

Mayo N. E., Wood-Dauphinee S., Cote R., Durcan L., Carlton J. (2002),"Activity, participation and quality of life 6 months post stroke,"*Archives of Physical Medicine and Rehabilitation,* 83:1035–1042.

McLaughlin M., Rizzo A., Jung Y., Peng W., Yeh S., Zhu W., (2005). " Haptics-Enhanced Virtual Environments for Stroke Rehabilitation," *Proc. IPSI*, Cambridge, MA.

Merians A, Jack D, Boian R, Tremaine M, Burdea GC, Adamovich SV, Recce M, Poizner H. (2002). “Virtual reality-augmented rehabilitation for patients following stroke,” *Phys Ther*.; 82:898–915.

Messier, J., Kalaska, J.F. (1999). "Comparison of variability of initial kinematics and endpoint of reaching movements." *Exp Brain Res*.5:139–152

Mihelj, M.; Nef, T. & Riener, R. (2006).“ARMin-Toward a Six DoF Upper Limb Rehabilitation Robot,” *IEEE International Conference on Biorobotics and Biomechatronics, Italy*, 1154- 1159

Mihelj M, Nef T., Riener R (2007).“ARMin II - 7 DoF rehabilitation robot: mechanics and kinematics,” *IEEE International Conference on Robotics and Automation* 4120–4125.

Miller LC, Ruiz-Torres, Ricardo, Stienen A H A, Dewald, J PA (2009). “A wrist and finger force sensor module for use during movements of the upper limb in chronic hemiparetic stroke,” *IEEE Transactions on Biomedical Engineering* 56(9): 2312-2317.

Monkman G. J. (1992). “Electrorheological Tactile Display”, Presence, MIT Press, Vol. 1, No. 2.

Mouawad M.R., Doust C.G., Max M.D., McNulty P.A. (2011)."Wii-based movement therapy to promote improved upper extremity function post-stroke: a pilot study," *J Rehabil Med* 43: 527-533.

Murgia A., Kyberd P.J., Chappell P.H., Light C.M. (2004). "Marker placement to describe the wrist movements during activities of daily living in cyclical tasks." *Clinical Biomechanics* (Bristol, Avon), 19(3):248-254.

Murphy TH, Corbett D (2009), "Plasticity during stroke recovery: from synapse to behaviour,". *Nat Rev Neurosci* 10:861– 872.

Nakayama H, Jorgensen H.S., Raaschou H.O., Olsen T.S.,(1994)," Recovery of upper extremity function in stroke patients: the Copenhagen Stroke Study,". *Arch Phys Med Rehabil* 1994; 75:394-398.

Nasa TLX, (2012), Accessed: 29 Feb. 12, NASA TLX: Task Load Index, http://humansystems.arc.nasa.gov/groups/TLX/tlxpublications.html

Nudo RJ (2006), "Mechanisms for recovery of motor function following cortical damage,". *Curr Opin Neurobiol* 16:638– 644.

O'Dell, M. W., C. C. Lin, et al. (2009). "Stroke rehabilitation: strategies to enhance motor recovery." Annu Rev Med 60:55-68.

O'Donnell M. J. , Xavier D., Liu L. , Zhang H. , Chin S. L., Rao-Melacini P., Rangarajan S., Islam S. , Pais P. , McQueen M. J , Mondo C. , Damasceno A., Lopez-Jaramillo P., Hankey G. J, Dans A. L, Yusoff K., Truelsen T., Diener H.C., Sacco R. L, Ryglewicz D. , Czlonkowska A., Weimar C., Wang X. , Yusuf S.,(2010),"Risk factors for ischaemic and intracerebral haemorrhagic stroke in 22 countries (the INTERSTROKE study): a case-control study,"The Lancet,Vol.376,Issue 9735.pp.112-123

O'Malley M. K., Ro T., Levin H.S.,(2006)."Assessing and Inducing Neuroplasticity With Transcranial Magnetic Stimulation and Robotics for Motor Function." *Arch Phys Med Rehabil*. 87(12): 59-66.

Pedretti, L.W., "Occupational Therapy: Practice Skills for Physical Dysfunction," 2nd ed., C.V. Mosby Co. St. Louis, Missouri, 1985.

Phelps A.M., Egert C.A., Bayliss J D (2009). "Multimedia at work. Games in the classroom at the Rochester Institute of Technology: A case study," *IEEE Multimedia, IEEE Computer Society*. 16(3): 82-88.

Porcher-Nedel, L., Thalmann, D., (1998). "Real Time Muscle Deformations Using MassSpring Systems", *Proc. CGI '98, IEEE Computer Society Press*.

Post MWM, de Witte LP, Schrijvers AJP. (1999)," Quality of life and the ICIDH: towards an integrated conceptual model for rehabilitation outcomes research," *Clin Rehabil*.1999;13:5–15

Prange G.B., Jannink M., Groothuis-Oudshoom C.G.M., Hermens H., Ijzerman M.J. (2006). "Systematic review of the effect of robot-aided therapy on recovery of hemiparetic arm after stroke," *Journal of Rehabilitation Research and Development* 43(2): 171-184.

P5 Glove, (1986), Accessed: 29 Feb. 12, http://p5glove.pbworks.com/w/page/6798892/Histroy

Rand, D., Kizony R., (2005). “Comparison of Two VR Platforms for Rehabilitation: Video Capture versus HMD,” *Presence: Teleoperators & Virtual Environments* 14(2): 147-160.

Rand D., Kizony R., Weiss P.T.(2008). "The Sony PlayStation II EyeToy: low-cost virtual reality for use in rehabilitation." *J Neurol Phys Ther.*32(4):155-63.

Reinkensmeyer D.J., Kahn L., Averbuch M., McKenna-Cole A., Schmit B.D., Rymer W.Z. (2000). “Understanding and treating arm movement impairment after chronic brain injury: Progress with ARM guide.,” *Journal of Rehab. Res and Developmet.* 37(6):653-662

Retrieved 14/10/09, 2009, from http://www.essentialreality.com.

Riva, G. (2002). “Virtual reality for health care: the status of research,” *CyberPsychology & Behavior* 5(3): 219–225.

Riva, G. (2005). “Virtual reality in psychotherapy: review,” *Cyberpsychol Behav* 8(3**):** 220-30.

Rizzo, A. A., Wiederhold B. , Riva G. , Der Z. C. V. (1998).“A Bibliography of Articles Relevant to the Application of Virtual Reality in the Mental Health Field,” *CyberPsychology & Behavior* 1(4): 411-411.

Rizzo A.A.(2002). “Virtual reality and disability: emergence and challenge,” *Disabil Rehabil*. 24:567–69.

Rizzo A.A., S. M., Kerns K, Mateer C. (2004). “Analysis of assets for virtual reality in neuropsychology,” *Neuropsychol Rehabil* 14: 207–239.

Rizzo A.A., Kim G.J. (2005). “A SWATAnalysis of the field of Virtual Reality and Therapy,” *Presence:Teleoperators and Virtual Environments* 14(2): 119-146.

Roetenberg, D., Baten, C.T., Veltink, P.H. (2007a). "Estimating body segment orientaton by applying inertial and magnetic sensing near ferromagnetic materials." *In IEEE Transactions of Neural Systems and Rehabilitation Engineering*.

Roetenberg, D., Baten, C.T., Veltink, P.H. (2007b)."Ambulatory Position and Orientation Tracking Using Magnetic and Inertial Sensing." *In Transaction on Biomedical Engineering. IEEE*

Rohrer B., Krebs H. I., Volpe B. T., Ferraro M., Fasoli S., Palazzolo J., Edelstein L., and Hogan N., (2002). “Robot-aided neuro-rehabilitation: From evidence-based to science-based rehabilitation,” *Topics Stroke Rehabil*., vol. 8, no. 4, pp. 54–68

Rosati G., Gallina P., Masiero S., Rossi A. (2005). “Design of a new 5 d.o.f. wire-based robot for rehabilitation,” *Proceedings of the 2005 IEEE 9th International Conference on Rehabilitation Robotics*: 430-433.

Rosati G, Gallina P., Masiero S (2007). “Design, implementation and clinical tests of a wire-based robot for neurorehabilitation,” *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 15(4**)** 560-569.

Rosati G, Bobrow J. E., Reinkensmeyer DJ (2008). “Compliant control of post-stroke rehabilitation robots: Using movement-specific models to improve controller performance,” *Proceedings of ASME International Mechanical Engineering Congress and Exposition*. 2: 167-174.

Rosati G., Secoli R., Zanotto D, Rossi A, Boschetti G (2009). “Planar robotic systems for upper-limb post-stroke rehabilitation,” *Proceedings of ASME International Mechanical Engineering Congress and Exposition,* 2: 115-124.

Rose F.D., A. E., Johnson DA (1996a). “Virtual reality: an assistive technology in neurological rehabilitation,” *Curr Opin Neurol* 9: 461-467.

Rose, F. D. (1996b). “Virtual reality in rehabilitation following traumatic brain injury,” *Proc. 1st Euro. Conf. Disability, Virtual Reality & Assoc. Tech*, Maidenhead, UK.

Rothbaum, B. O., & Hodges, L. F. (1999). “The use of virtual reality exposure in the treatment of anxiety disorders,” *Behavior Modification* 23 (4): 507-526.

Sanchez-Vives, M. V. a. M. S. (2005). “From presence to consciousness through virtual reality,” *Nat Rev Neurosci* 6(4): 332-339.

Sanchez RJ, Liu J., Rao S, Shah P, Smith R, Rahman T, Cramer SC, Bobrow JE, Reinkensmeyer DJ (2006). “Automating arm movement training following severe stroke: Functional exercises with quantitative feedback in a gravity-reduced environment,” *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 14(3): 378-389.

Saposnik G., Teasell R., Mamdani M., Hall J., McIlroy W.,(2010). "Effectiveness of Virtual Reality Using Wii Gaming Technology in Stroke Rehabilitation," *Stroke* 41: 1477-1484

Scheepers, F., Parent, R. E., Carlson, W., May , S. F.(1997). "Anatomy-based modeling of the human musculature." *In Computer Graphics (SIGGRAPH roceedings),* 163–172

Schettino L.F., Adamovich S.V., Poizner H. (2003). "The role of visual feedback in the determination of hand coordination during grasping."*Exp Brain Res*. 151:158-66

Schleihauf, R.E. (2004). "Biomechanics of human movement (1st ed.)." Bloomington, In Author House

Schultheis MT, Mourant RR.(2001). "Virtual reality and driving: The road to better assessment of cognitively impaired populations," *Presence Teleoper Virtual Environ*.;10: 436-44.

Scott S.H., (2004)., Accessed :29 February 2012, http://www.nature.com/nrn/journal/v5/n7/box/nrn1427_BX1.html

Sderkvist, J. (1994). "Micromachined gyroscopes," *Sensors Actuators*, 43:65- 71

Shreiner, D., Woo, M., Neider, J. and Davis, T., (2003). "OpenGL Programming Guide." vo1.4. Addison Wesley Professional.

Sietsema JM, Nelson D., Mulder RM (1993)."The use of game to promote arm reach in persons with traumatic brain injury," *Am J Occup Ther* 47: 19-24.

Sife, W. (1998). "After Stroke:Enhancing Quality of life," *The Haworth Press, Inc*. New York.London.

Simonidis, C., Stein, T., Bauer, F. , Fischer, A. ,Schwameder, H. , Seemann, W. (2009)."Determining principles of human motionby combining motion analysis and motion synthesis." *In Proceedings of the IEEE-RAS International Conference on Humanoid Robots. Paris (France)*

Sivak M, Mavroidis C, Holden MK. (2009).“Design of a low cost multiple user virtual environment for rehabilitation (MUVER) of patients with stroke.’’ *Stud Health Technol Inform*.142:319-24.

Sukal TM, Ellis MD, Dewald JPA. (2007). “Shoulder abduction-induced reductions in reaching work area following hemiparetic stroke: neuroscientific implications,” *Exp Brain Res* 183: 215–223.

Stilson,T.(1996).Accelerometer (Analog Devices ADXL50). URL://www.cs.princeton.edu/courses/archive/fall07/cos436/sensors/node9.html

Studenski, S., Carlson, M.C., Fillit, H., Greenough, W.T., Kramer, A. and Rebok, G.W. (2006). “From bedside to bench: Does mental and physical activity promote cognitive vitality in late life?, ” Science Aging Knowledge Environment, (10),21.

Sunderland A, Tinson D., Bradley L (1992). “Enhanced physical therapy for arm function after stroke:a one year follow-up study,” *J Neurol Neurosurg Psychiatry* 57: 856-858.

Squire, L. R., Albright T., (2009). Encyclopedia of neuroscience, San Diego: Academic Press

Stone, R. J. (1995). “The reality of virtual reality,” *World Class Design to Manufacture* 2(4) 11–17

Stroke Association, Accessed 12/01/2012, *http://www.strokeassociation.org*

Sveistrup H, M. J., Thornton M, Marshall S, Finestone H, McCormick A, Babulic K, Mayhew A (2003). “Experimental studies of virtual reality-delivered compared to conventional exercise programs for rehabilitation,” *Cyberpsychol Behav* 6: 243-249.

Tao Y, H. H., Zhou H (2007). “Integration of vision and inertial sensors for 3D arm motion tracking in home-based rehabilitation,” *International Journal of Robotics Research* 26(6): 607-624.

Taub E., M. N. E., Novack T. A., Cook E. W., Fleming W. C., Nepomuceno C. S. (1993). “Technique to improve chronic motor deficit after stroke,” *Archives of Physical Medicine and Rehabilitation* 74(4): 347-354.

Taylor, C. L., (1954). "The biomechanics of the normaland of the amputated upper extremity, Chapter 7 in Klopsteg and Wilson's Human limbs and their substitutes, " McGraw-Hill, New York.

Teasell R, Foley N., Salter K, Bhogal RS, Bayona N, Jutai J, Speechley M. (2007). “Evidence based Review of stroke rehabilitation,” *Retrieved 14/10/09, 2009, from http://www.ebrsr.com.*

Tennant, A., et al. (1997), 'Outcome following stroke', Disabil Rehabil, 19 (7), 278-84

Thielman, G., Terry, K., Gentile, A.M., (2008) "Rehabilitation of reaching after stroke:comparing 2 training protocol utilizing trunkrestraint." Neurorehabil Neural Repair. 22:697-705

Thompson J., Kuchera-Morin J., Novak M., Overholt D., Putnam L., Wakefield G., Smith W. (2009). “The Allobrain: An interactive, stereographic, 3D audio, immersive virtual world,” *International Journal of Human Computer Studies* 67(11) 934-946.

Thorngren, M., Westling, B., & Norrving, B. (1990). "Outcome after stroke in patients discharged to independent living,". *Stroke*, 21(2), 236-240

Trombly C.A., Wu C.Y., (1999). "Effect of rehabilitation tasks on organization of movement after stroke." American Journal of Occupational Therapy,53(4):333-344

Van der Lee JH, De Groot V., Beckerman H (2001). “The intra and interrater reliability of the action research arm test:a practical test of upper extremity functions in patients with stroke*,” Arch Phys Med Rehabil* 82: 14-19.

Van Vliet P, Kerwin D., Sheridan M (1995). “The influence of goals on the kinematics of reaching following stroke,” *Neurol Rep* 19: 11-16.

Verbunt J. A., Seelen H. A.M., Ramos F.P,B. Michielsen H.M.,W. Wetzelaer L, M. Moennekens, (2008), “Mental practice-based rehabilitation training to improve arm function and daily activity performance in stroke patients: a randomized clinical trial”, *BMC Neurol*.2008; 8: 7

Viau, A., A. G. Feldman, B. J. McFadyen and M. F. Levin (2004), “Reaching in reality and virtual reality: a comparison of movement kinematics in healthy subjects and in adults with hemiparesis.” *J Neuroengineering Rrehabil* 1(1):11

Vicon (2011), Accessed 29 Feb 2011, <http://www.vicon.com/products/viconmx.html>

Volpe, B. T., P. T. Huerta, et al. (2009). "Robotic devices as therapeutic and diagnostic tools for stroke recovery." Arch Neurol 66(9): 1086-90.

Wade DT, Langton-Hewer R, Wood VA, Skilbeck CE, Ismail HM. (1983). “The hemiplegic arm after stroke: measurement and recovery,”Journal of Neurology, *Neurosurgery and Psychiatry* ;46(6):521-4.

Wade DT, Skilbeck C, Langton Hewer R.,(1989)," Selected cognitive losses after stroke:frequency recovery and prognostic importance,".*Int Disabil Stud*.1989;11:34–39

Ware, C., & Balakrishnan, R. (1994). Reaching for objects in VR displays: Lag and frame rate. *ACM Transactions on Computer-Human Interaction*. 1(4). p. 331-356.

Ware, C., & Lowther, K. (1997). Selection using a one-eyed cursor in a fish-tank VR environment. *ACM Transactions on Computer Human Interaction*. 4(4). p. 309-322.

Weiss P.H., Marshall J.C., Wunderlich G., Tellmann L., Halligan P.W., Freund H.J.,(2000). "Neural consequences of acting in near versus far space: a physiological basis for clinical dissociations." *Brain* 2000; 123:2531-41

Weiss P.L., K. Kiznoy, Feintuch U., Katz N. (2006). “Virtual reality in neurorehabilitation Textbook of neural repair and neurorehabilitation,” C. L. Selzer ME, Gage FH, Clarke S, Duncan PW, *New York: Cambridge Press*.

Whitrow, R. (2008). "OpenGL Graphics Through Applications." Springer

Wickenden, D.K.; Givens, R.B.; Osiander, R.; Champion, J.L.; Oursler, D.A.; Kistenmacher, T.J. (1998). "MEMS-based resonating xylophone bar magnetometers. *Micromach. Devices Compon*. IV: 350–358.

Witmer BG, Singer MJ. (1998). “Measuring presence in virtual environments: A Presence Questionnaire,” *MIT Press Journals-Presence: Teleoperators and Virtual Environments* 7(3): 225-240

Wolf SL, C. P., Ellis M, Archer AL, Morgan B, Piacentino A. (2001). “Assessing Wolf Motor Function Test as outcome measure for research in patients after stroke,” *Stroke* 32: 1635-1639.

Wu, C.Y. (1997). "Effects of context on movement kinematics in adults with and without cerebral vascular accident." *Unpublished doctoral dissertation, Boston niversity, Boston*.

Wu C, Trombly C., lin k (2000).“A kinematic study of contextual effects on reaching performance in persons with and without stroke: influences of object availability,” *Arch Phys Med Rehabil* 81: 95-101.

Xydas EG, Louca LS (2009). “Upper limb assessment of people with multiple sclerosis with the use of a haptic nine hole peg-board test,” *Proceedings of the 9th Biennial Conference on Engineering Systems Design and Analysis*. 2**:** 159-166.

Yang C.C. , Hsu Y. L. (2010), “A review of accelerometry-based wearable motion detector for physical activity monitoring,” Sensors, vol.10, pp.7772-7788,

Yavuzer, G., Senel, A. et al (2008). "Playstation eyetoy games improve upper extremity-related motor functioning in subacute stroke: a randomized controlled clinical trial," *Eur J Phys Rehabil Med*, 44 (3), 237-244.

Yoshimoto,S. (1992) “Ballerinas generated by a personal computer,” The Journal of Visualization and Computer Animation, 3(1):85–90

Zhai, S. (1995). "Human performance in six degree-of-freedom input control." *Ph.D. Thesis*. University of Toronto.

Zhang L, Abreu BC, Masel B, Scheibel RS, Christiansen CH, Huddleston N, Ottenbacher K.J.(2001).“Virtual reality in the assessment of selected cognitive function after brain injury,” *Am J Phys Med Rehabil*.80:597–604.

Zhao L., Xu D. (2009). “Immersive display and interactive techniques for the modeling and rendering of virtual heritage environments,” *International Conference on Information Management and Engineering***:** 601-606.

Zhou, H. T., Yaqin; Hu, Huosheng (2007). “Integration of vision and inertial sensors for 3D arm motion tracking in home-based rehabilitation,” *International Journal of Robotics Research* 26(6): 607-624.

Zimmerman, T. G., (1982)..“Optical flex sensor,” *U.S. Patent* 4 542 291. US

5DT Glove, (2005), Accessed : 29 Feb. 12, http://www.5dt.com/products/pdataglove5u.html

APPENDICES

APPENDIX 1

Simulation Algorithm

Robot.cpp

```
#include "robot.h"
#include<cmath>

#include "Project.h"
#include "DataGlove.h"


#include<stdio.h>
#include <stdlib.h>
#include<conio.h>
#include<math.h>
#include <iostream>

#include <fstream>

/*************************/

int* ShowValues();      // global variable for Data Glove
extern float angle[9]; // global variable for Data Glove

/*************************/



//int L1=18;
```

```
//int L2=15;

int L1=10;
int L2=8;



int E_X=L1;
int E_Y=0;
int E_Z=0;

int W_X=L2;
int W_Y=0;
int W_Z=0;

//double rx = 0.0;
//double ry = 0.0;

float l[] = { 0.0,  25.0, -25.0 }; // Coordinates of the light source
float n[] = { 0.0,  -1.0, 0.0 }; // Normal vector for the plane
float e[] = { 0.0, -60.0, 0.0 }; // Point of the plane

//void console_read();

// This function is called whenever the object needs to be drawn
// (For the shadow and itself; for each frame twice)



 /* position Estimation variables*/

    double a,d,g,b,E,h,c,f,i;

      double EP_X,EP_Y,EP_Z;


      double L,m,N,o,p,q,r,s,t;
```

```
    double WP_X,WP_Y,WP_Z;

/* position Estimation variables end*/

void Upper_Arm_VE()
{
          // Data from Sensors
    int* f = ShowValues(); // Data from Glove

    GetData();

 //printf("%lf %lf %lf\n",angle[0],angle[1],angle[2]);
 //printf("%lf %lf %lf\n",angle[3],angle[4],angle[5]);

      GLUquadricObj *qobj1 = gluNewQuadric();
      GLUquadricObj *qobj2 = gluNewQuadric();
      GLUquadricObj *qobj3 = gluNewQuadric();

      gluQuadricDrawStyle(qobj1,GLU_FILL);
      gluQuadricDrawStyle(qobj2,GLU_FILL);
      gluQuadricDrawStyle(qobj3,GLU_FILL);

/******Draw Upper Extremity*********/

      glPushMatrix();

            glRotatef(angle[2],0.0f,1.0f,0.0f);
            glRotatef(angle[1],1.0f,0.0f,0.0f);
```

```
        glRotatef(angle[0],0.0f,0.0f,1.0f);

      glPushMatrix();
        gluDisk(qobj3,0.0f,3.0f,10.0f,10.0f);
        gluCylinder(qobj1,1.5f,1.0f,L1,10.0f,10.0f);
glPopMatrix();

      glTranslatef(0.0f,0.0f,L1);
        glRotatef(angle[5]-(angle[2]),0.0f,1.0f,0.0f);
        glRotatef(angle[4]-(angle[1]),1.0f,0.0f,0.0f);
        glRotatef(angle[3]-(angle[0]),0.0f,0.0f,1.0f);


  glPushMatrix();
        gluCylinder(qobj1,1.0,0.8,L2,10,10);
  glPopMatrix();




  /* Hand and Fingers */

  glPushMatrix();

    glTranslatef(0.0f,0.0f,L2);
        //glColor4f(0.50f,0.50f,1.0f,0.2f);

  glPushMatrix();
    glScalef(1.0f, 0.42f, 1.0f);
        //glutSolidSphere(1.0,10,10);
        glutSolidCube(2.5);

glPopMatrix();


/* First Finger----THUMB*/

glPushMatrix();
```

```
    //glTranslated(1.4,0.0,2.1);
      glTranslatef(1.4f,0.0f,1.1f);
        //glRotated(90,0,1,0);
        glRotatef(f[0],1.0f,0.0f,0.0f);
     // glColor4f(0.50f,0.50f,1.0f,0.2f);

 glPushMatrix();
   //glScalef(0.1, 0.1, 1.0);
       //glutSolidCube(2.5);

       gluCylinder(qobj1,0.2f,0.2f,2.5f,10.0f,10.0f);
 glPopMatrix();

    glTranslatef(0.0f,0.0f,2.1f);
        glRotatef(f[0],1.0f,0.0f,0.0f);
     // glColor4f(0.50f,0.50f,1.0f,0.2f);

 glPushMatrix();
   //glScalef(0.1, 0.1, 1.0);
       //glutSolidCube(2.1);
 glutSolidSphere(0.4f,10.0f,10.0f);
 gluCylinder(qobj1,0.2f,0.1f,2.3f,10.0f,10.0f);
 glPopMatrix();

      glTranslatef(0.0f,0.0f,2.1f);
        glRotatef(f[0],1.0f,0.0f,0.0f);
     // glColor4f(0.50f,0.50f,1.0f,0.2f);

 glPushMatrix();
   //glScalef(0.1, 0.1, 1.0);
       //glutSolidCube(2.0);
 glutSolidSphere(0.2f,10.0f,10.0f);
 gluCylinder(qobj1,0.1f,0.05f,2.0f,10.0f,10.0f);
 glPopMatrix();

glPopMatrix();

 /* second finger */
```

```
glPushMatrix();
     glTranslatef(0.8f,0.0f,1.1f);
         glRotatef(f[1],1.0f,0.0f,0.0f);
      //glColor4f(0.50f,0.50f,1.0f,0.2f);

  glPushMatrix();
    //glScalef(0.1, 0.1, 1.0);
        //glutSolidCube(2.0);
      gluCylinder(qobj1,0.2f,0.2f,2.5f,10.0f,10.0f);
  glPopMatrix();

     glTranslatef(0.0f,0.0f,2.1f);
         glRotatef(f[1],1.0f,0.0f,0.0f);
       //glColor4f(0.50f,0.50f,1.0f,0.2f);

  glPushMatrix();
    //glScalef(0.1, 0.1, 1.0);
        //glutSolidCube(2.0);
       glutSolidSphere(0.4f,10.0f,10.0f);
       gluCylinder(qobj1,0.2f,0.1f,2.3f,10.0f,10.0f);
  glPopMatrix();

       glTranslatef(0.0f,0.0f,2.1f);
         glRotatef(f[1],1.0f,0.0f,0.0f);
       //glColor4f(0.50f,0.50f,1.0f,0.2f);

  glPushMatrix();
    //glScalef(0.1, 0.1, 1.0);
        //glutSolidCube(2.0);
       glutSolidSphere(0.2f,10.0f,10.0f);
       gluCylinder(qobj1,0.1f,0.05f,2.0f,10.0f,10.0f);
  glPopMatrix();

glPopMatrix();

  /* third finger */
```

```
  glPushMatrix();
    glTranslatef(0.0f,0.0f,1.1f);
        glRotated(f[2],1.0f,0.0f,0.0f);
      //glColor4f(0.50f,0.50f,1.0f,0.2f);

 glPushMatrix();
   //glScalef(0.1, 0.1, 1.0);
       //glutSolidCube(2.0);
      gluCylinder(qobj1,0.2f,0.2f,2.5f,10.0f,10.0f);
 glPopMatrix();

    glTranslatef(0.0f,0.0f,2.1f);
        glRotatef(f[2],1.0f,0.0f,0.0f);
     //glColor4f(0.50f,0.50f,1.0f,0.2f);

 glPushMatrix();
   //glScalef(0.1, 0.1, 1.0);
       //glutSolidCube(2.0);
        glutSolidSphere(0.4f,10.0f,10.0f);
      gluCylinder(qobj1,0.2f,0.1f,2.3f,10.0f,10.0f);
 glPopMatrix();


      glTranslatef(0.0f,0.0f,2.1f);
        glRotated(f[2],1,0,0);
     //glColor4f(0.50f,0.50f,1.0f,0.2f);

 glPushMatrix();
   //glScalef(0.1, 0.1, 1.0);
       //glutSolidCube(2.0);
      glutSolidSphere(0.2f,10.0f,10.0f);
      gluCylinder(qobj1,0.1f,0.05f,2.0f,10.0f,10.0f);
 glPopMatrix();

glPopMatrix();

 /* fourth finger */
```

```
  glPushMatrix();
     glTranslatef(-0.8f,0.0f,1.1f);
         glRotatef(f[3],1.0f,0.0f,0.0f);
     // glColor4f(0.50f,0.50f,1.0f,0.2f);

  glPushMatrix();
    //glScalef(0.1, 0.1, 1.0);
        //glutSolidCube(2.0);
      gluCylinder(qobj1,0.2f,0.2f,2.5f,10.0f,10.0f);
  glPopMatrix();

     glTranslatef(0.0f,0.0f,2.1f);
         glRotatef(f[3],1.0f,0.0f,0.0f);
     //glColor4f(0.50f,0.50f,1.0f,0.2f);

  glPushMatrix();
    //glScalef(0.1, 0.1, 1.0);
        //glutSolidCube(2.0);
       glutSolidSphere(0.4f,10.0f,10.0f);
       gluCylinder(qobj1,0.2f,0.1f,2.3f,10.0f,10.0f);
  glPopMatrix();

       glTranslated(0.0,0.0,2.1);
         glRotated(f[3],1,0,0);
       //glColor4f(0.50f,0.50f,1.0f,0.2f);

  glPushMatrix();
    //glScalef(0.1, 0.1, 1.0);
        //glutSolidCube(2.0);
       glutSolidSphere(0.2,10,10);
       gluCylinder(qobj1,0.1,0.05,2.0,10,10);
  glPopMatrix();

glPopMatrix();

  /* fifth finger */
```

```
  glPushMatrix();
     glTranslated(-1.4,0.0,1.1);
         glRotated(f[4],1,0,0);
       //glColor4f(1.0f,0.0f,1.0f,0.2f);

  glPushMatrix();
    //glScalef(0.1, 0.1, 1.0);
        //glutSolidCube(2.0);
        gluCylinder(qobj1,0.2,0.2,2.5,10,10);
  glPopMatrix();

     glTranslated(0.0,0.0,2.1);
         glRotated(f[4],1,0,0);
       //glColor4f(1.0f,0.0f,1.0f,0.2f);

  glPushMatrix();
    //glScalef(0.1, 0.1, 1.0);
        //glutSolidCube(2.0);
       glutSolidSphere(0.4,10,10);
       gluCylinder(qobj1,0.2,0.1,2.3,10,10);
  glPopMatrix();


     glTranslated(0.0,0.0,2.1);
         glRotated(f[4],1,0,0);
       //glColor4f(1.0f,0.0f,1.0f,0.2f);

  glPushMatrix();
    //glScalef(0.1, 0.1, 1.0);
        //glutSolidCube(2.0);
       glutSolidSphere(0.2,10,10);
       gluCylinder(qobj1,0.1,0.05,2.0,10,10);
  glPopMatrix();

glPopMatrix();
```

```
//////////////////////////////
      glPopMatrix(); ///for the hand


      glPopMatrix();


GLdouble mvmatrix[16];

/******Draw Upper Extremity Complete*****/

glGetDoublev (GL_MODELVIEW_MATRIX, mvmatrix);

}

void position_estimation(void)
{
   GetData();


a=cos(angle[1])*cos(angle[2]);
d=cos(angle[1])*sin(angle[2]);
g=-sin(angle[1]);

b=(sin(angle[0])*sin(angle[1])*cos(angle[2])-
cos(angle[0])*sin(angle[2]));
E=(sin(angle[0])*sin(angle[1])*sin(angle[2])+cos(angle[0])*cos(angle[2]
));
h=sin(angle[0])*cos(angle[1]);

c=(cos(angle[0])*sin(angle[1])*cos(angle[2])+sin(angle[0])*sin(angle[2]
));
f=(cos(angle[0])*sin(angle[1])*sin(angle[2])-
sin(angle[0])*cos(angle[2]));
i=cos(angle[0])*cos(angle[1]);
```

```
EP_X=a*E_X+d*E_Y+g*E_Z;
EP_Y=b*E_X+E*E_Y+h*E_Z;
EP_Z=c*E_X+f*E_Y+i*E_Z;


L=cos(angle[1]-angle[4])*cos(angle[2]-angle[5]);
m=cos(angle[1]-angle[4])*sin(angle[2]-angle[5]);
N=-sin(angle[1]-angle[4]);

o=(sin(angle[0]-angle[3])*sin(angle[1]-angle[4])*cos(angle[2]-
angle[5])-cos(angle[0]-angle[3])*sin(angle[2]-angle[5]));
p=(sin(angle[0]-angle[3])*sin(angle[1]-angle[4])*sin(angle[2]-
angle[5])+cos(angle[0]-angle[3])*cos(angle[2]-angle[5]));
q=sin(angle[0]-angle[3])*cos(angle[1]-angle[4]);

r=(cos(angle[0]-angle[3])*sin(angle[1]-angle[4])*cos(angle[2]-
angle[5])+sin(angle[0]-angle[3])*sin(angle[2]-angle[5]));
s=(cos(angle[0]-angle[3])*sin(angle[1]-angle[4])*sin(angle[2]-
angle[5])-sin(angle[0]-angle[3])*cos(angle[2]-angle[5]));
t=cos(angle[0]-angle[3])*cos(angle[1]-angle[4]);




WP_X=L*W_X+m*W_Y+N*W_Z+EP_X;
WP_Y=o*W_X+p*W_Y+q*W_Z+EP_Y;
WP_Z=r*W_X+s*W_Y+t*W_Z+EP_Z;




/*
                      FILE* k;

      if((k=fopen("Elbow_Position.txt","ab"))==NULL)
                              {
```

```
                              printf("could not open file");
                              getch();
                              exit(1);
                             }



    //printf("Elbow co-ordinate: %f %f %f", EP_X,EP_Y,EP_Z);
      fprintf(k,"%f %f %f\n\n",EP_X,EP_Y,EP_Z);
      printf("\n\n\n");

      fclose(k);
*/
                           FILE* W;

      if((W=fopen("Wrist_Position.txt","ab"))==NULL)
                             {
                              printf("could not open file");
                              getch();
                              exit(1);
                             }




    printf("Elbow co-ordinate: %f %f %f", WP_X,WP_Y,WP_Z);
      fprintf(W,"%f %f %f\n\n",WP_X,WP_Y,WP_Z);
      printf("\n\n\n");

      fclose(W);







}
```

```
void glShadowProjection(float * l, float * e, float * n)
{
  float d, c;
  float mat[16];

  // These are c and d (corresponding to the tutorial)

  d = n[0]*l[0] + n[1]*l[1] + n[2]*l[2];
  c = e[0]*n[0] + e[1]*n[1] + e[2]*n[2] - d;

  // Create the matrix. OpenGL uses column by column
  // ordering

  mat[0]  = l[0]*n[0]+c;
  mat[4]  = n[1]*l[0];
  mat[8]  = n[2]*l[0];
  mat[12] = -l[0]*c-l[0]*d;

  mat[1]  = n[0]*l[1];
  mat[5]  = l[1]*n[1]+c;
  mat[9]  = n[2]*l[1];
  mat[13] = -l[1]*c-l[1]*d;

  mat[2]  = n[0]*l[2];
  mat[6]  = n[1]*l[2];
  mat[10] = l[2]*n[2]+c;
  mat[14] = -l[2]*c-l[2]*d;

  mat[3]  = n[0];
  mat[7]  = n[1];
  mat[11] = n[2];
  mat[15] = -d;

  // Finally multiply the matrices together *plonk*
  glMultMatrixf(mat);
}
```

```
void init()
{
   glClearColor (0.0, 0.0, 0.0, 0.0);
   glShadeModel (GL_FLAT);
}


void Robot_Display()
{

  glClearColor(0.0,0.6,0.9,0.0);
  glClear(GL_COLOR_BUFFER_BIT|GL_DEPTH_BUFFER_BIT);

  glLightfv(GL_LIGHT0, GL_POSITION, l);

  glDisable(GL_CULL_FACE);
  glDisable(GL_LIGHTING);

  glColor3f(1.0,1.0,0.0);
  glBegin(GL_POINTS);
  glVertex3f(l[0],l[1],l[2]);
  glEnd();

  // First, we draw the plane onto which the shadow should fall
  // The Y-Coordinate of the plane is reduced by 0.1 so the plane is
  // a little bit under the shadow. We reduce the risk of Z-Buffer
  // flittering this way.
  glColor3f(0.8,0.8,0.8);
  glBegin(GL_QUADS);
  glNormal3f(0.0,1.0,0.0);

  glVertex3f(-1300.0,e[1]-0.1, 1300.0);
  glVertex3f( 1300.0,e[1]-0.1, 1300.0);
  glVertex3f( 1300.0,e[1]-0.1,-1300.0);
  glVertex3f(-1300.0,e[1]-0.1,-1300.0);

  glEnd();
```

```
position_estimation();


  // Draw the object that casts the shadow
  glPushMatrix();
  //glRotatef(ry,0,1,0);
  //glRotatef(rx,1,0,0);
  glEnable(GL_LIGHTING);
  //glColor3f(0.0,0.0,0.8);
  glColor3f(0.4,0.4,0.4);
  Upper_Arm_VE();
  glPopMatrix();

  // Now we draw the shadow
  glPushMatrix();
  glShadowProjection(l,e,n);
  //glRotatef(ry,0,1,0);
  //glRotatef(rx,1,0,0);
  glDisable(GL_LIGHTING);
  glColor3f(0.4,0.4,0.4);
  Upper_Arm_VE();
  glPopMatrix();


  /*Table*/

glPushMatrix();
     glTranslatef(0.0f,-12.0f,62.0f);
       glColor3d(1.10,0.30,0.0);

       glScaled(25.0,.99,8.0);
       glutSolidCube(2);
glPopMatrix();


glPushMatrix();
```

```
     glTranslatef(-20.0f,-25.0f,62.0f);
       //glColor3d(0.10,0.0,1.0);
       glColor3d(1.10,0.30,0.0);
       glScaled(.99,12.5,.99);
       glutSolidCube(2);
glPopMatrix();

glPushMatrix();
     glTranslatef(20.0f,-25.0f,62.0f);
       //glColor3d(0.10,0.0,1.0);
       glColor3d(1.10,0.30,0.0);
       glScaled(.99,12.5,.99);
       glutSolidCube(2);
glPopMatrix();

/*Table Ends*/

/* Objects*/

glPushMatrix();
     glTranslatef(-20.0f,-7.5f,62.0f);
       glRotatef(-60.0f,0.0f,1.0f,0.0f);
       glColor3d(0.20,0.50,2.0);
       glutSolidTeapot(3);
glPopMatrix();

glPushMatrix();
     glTranslatef(20.0f,-8.0f,62.0f);
       glColor3d(0.20,0.50,2.0);
       glutSolidSphere(3,10,10);
glPopMatrix();

glPushMatrix();
     glTranslatef(0.0f,-8.0f,62.0f);
      glColor3d(0.20,0.50,2.0);
       glutSolidCube(4);
glPopMatrix();
```

```
/* Objects End*/

/* Walls */
glPushMatrix();
     glTranslatef(65.0f,-10.0f,32.0f);
       glColor3d(1.10,0.30,1.0);
       glScaled(1.19,30.99,50.0);
       glutSolidCube(2);
glPopMatrix();

glPushMatrix();
     glTranslatef(0.0f,-10.0f,75.0f);
       glColor3d(1.10,0.30,1.0);
       glScaled(65.19,30.99,1.99);
       glutSolidCube(2);
glPopMatrix();

glPushMatrix();
     glTranslatef(-65.0f,-10.0f,32.0f);
       glColor3d(1.10,0.30,1.0);
       glScaled(1.19,30.99,50.0);
       glutSolidCube(2);
glPopMatrix();

  glutSwapBuffers();
  }
void idle()
{

  Robot_Display();
}

void reshape (int width, int height)
{
  glViewport(0, 0, (GLsizei)width, (GLsizei)height);
  glEnable(GL_NORMALIZE);
  glEnable(GL_LIGHTING);
  glEnable(GL_COLOR_MATERIAL);
```

```
  glEnable(GL_DEPTH_TEST);
  glEnable(GL_LIGHT0);
  glEnable(GL_TEXTURE_2D);
  glMatrixMode(GL_PROJECTION);
  glLoadIdentity();
  gluPerspective(60, (GLfloat)width / (GLfloat)height, 1.0, 1000.0);
  glMatrixMode(GL_MODELVIEW);
  glLoadIdentity();
  gluLookAt (0.0, 5.0, -12.0, 0.0, 0.0, 0.0, 0.0, 1.0, 0.0);
}
```

Main.cpp

```
///*****SENSOR ***/////


#include "main.h"
#include "stdafx.h"
#include "windows.h"


/*glove header and defines*/

#include "Project.h"
#include "DataGlove.h"

#include <glui.h>

Project *proj ;
int gloveid1;



int* ShowValues();


/*Sensor agles*/
```

```
float angle[9];

/*VHand Glove Output*/

int main_window;
int   wireframe = 0;
int   segments = 8;

#include "objbase.h"    /* Needed for COM functionality of Sensor */

/* import functions in MT object  for Sensor*/
#include "IMTObj.h"
/* GUIDs of MT object for Sensor */
#include "IMTObj_i.c"


/* return values for MT_GetOrientation function for Sensor */
#define MT_NEWDATA                  1
#define MT_NODATA            2
#define MT_NOSENSORID        3
#define MT_INCOMPLETE        4
#define MT_CHECKSUMERROR     5
#define MT_NOPORT            6
#define MT_NOCALIBVALUES     7
#define MT_POWERLOSS         8

/*output possiblities for MT object for Sensor */
#define MT_LOGQUATERNION     0
#define MT_LOGEULER          1
#define MT_LOGROTMATRIX 2

/*Global pointer to the MTObj COM Interface for Sensor */
IMotionTracker* pMT;

/* Sensor Output data format */
short g_nMode = MT_LOGEULER;
```

```
/* SENSOR Filter Set Up Function */

void SetupFilter()
{
	// Set MTObj COM object options
	short m_bLogCalibratedData = FALSE;

	// Set MTObj COM object variables
	float fGain = 1.0;
	short nCorInterval = 1;
	float fRho = 1.0;
	short nPortNumber = 7;
	//short nTimeStampOutput = 1;

	// Create instance of MTObj COM object
	printf("Create instance of MotionTracker object...");
	HRESULT   hRes   =   CoCreateInstance(CLSID_MotionTracker,   NULL,
CLSCTX_SERVER, IID_IMotionTracker, (void**) &pMT);
	if (FAILED(hRes))
	{
		printf("Error %x in CoCreateInstance for MT object!",hRes);
		return;
	}
	else
		printf("done\n\n");


	printf("Setting filter parameters...");
	// Optional settings
	pMT->MT_SetCalibratedOutput(m_bLogCalibratedData);

	// Set Gain, Correction interval and Rho
	pMT->MT_SetFilterSettings(fGain,nCorInterval,fRho);

	// Required settings
```

```
	pMT->MT_SetOutputMode(g_nMode);

	// Set COM port number (1-15) where MT9 is attached
	pMT->MT_SetCOMPort(nPortNumber);

	// Set TimeStamp to be included in orientation data
      //pMT->XM_SetTimeStampOutput(nTimeStampOutput);

	printf("done\n\n");
}

/* Sensor Data Acquisition Function*/

bool GetData()
{
	float fOrientationData[9] = {0};
	VARIANT OrientationBuffer;
	void* pDest;
	short nNew = 0;

	BOOL bNewData = FALSE;

	pMT->MT_GetOrientationData(&nNew, &OrientationBuffer);
	if (nNew == MT_NEWDATA)
	{
		// Check if array is not empty
		if (OrientationBuffer.vt != VT_EMPTY)
		{
			// Retrieve pointer to array data
			HRESULT                      hr                   =
SafeArrayAccessData(OrientationBuffer.parray, &pDest);
			//  One  dimensional  array.  Get  the  bounds  for  the
array.

			if (SUCCEEDED(hr))
			{
				__try{
```

```
                    // Copy data from the VARIANT array to
the local fData array

      memcpy(fOrientationData,pDest,(OrientationBuffer.parray-
>rgsabound->cElements * sizeof(float)));
                              bNewData = TRUE;
                        }
                        __except(GetExceptionCode()               ==
STATUS_ACCESS_VIOLATION){
                              bNewData = FALSE;
                        }



      SafeArrayUnaccessData(OrientationBuffer.parray);      //
Invalidate pointer

                        // Variant must be cleared. This also destroys
the SafeArray
                        VariantClear(&OrientationBuffer);

                        //  fOrientationData  now  contains  orientation
data is bNewData = true
                        // Can be logged to file or written to screen
(see below)

                        if (g_nMode == MT_LOGEULER)
                        {
                              angle[0]=fOrientationData[0];
                              angle[1]=fOrientationData[1];
                              angle[2]=fOrientationData[2];
                              angle[3]=fOrientationData[3];
                              angle[4]=fOrientationData[4];
                              angle[5]=fOrientationData[5];
                              angle[6]=fOrientationData[6];
                              angle[7]=fOrientationData[7];
                              angle[8]=fOrientationData[8];
```

```
                    //printf("%lf                    %lf
%lf\n",angle[0],angle[1],angle[2]);

                }

                bNewData = FALSE;

                return TRUE;
            }
            else
                return FALSE;
        }
        else
            return FALSE;
    }
    else if (nNew != 0)
    {
        // Check if error was reported by MotionTracker object
        switch(nNew) {
        case MT_NODATA:
            printf("No Data On COM Port\n\n");
            break;
        case MT_NOSENSORID:
            printf("No Sensor ID Received From Sensor\n\n");
            break;
        case MT_INCOMPLETE:
            printf("Incomplete    Data    Received    (Connection
Lost)\n\n");
            break;
        case MT_CHECKSUMERROR:
            printf("Checksum Error\n\n");
            break;
        case MT_NOPORT:
            printf("COM Port Could Not Be Opened\n\n");
            break;
        case MT_NOCALIBVALUES:
            printf("XMU File With Calibration Data Could Not Be
Read or \nMTS Data With Calibration Data Not Set\n\n");
```

```
                break;
            case MT_POWERLOSS:
                printf("Power  Supply  To  The  Sensor  Was  Probably
Interupted\n\n");
                break;
            }

            return FALSE;
        }
        else
            return TRUE;

}



/* MAIN FUNCTION */



int* ShowValues()
{
DataGlove *dg1 = proj->GetDataGlove(gloveid1);
//dg1->ResetValue();
int *f = new int[5];



            // raw data in the buffer, compute real values
        float media[20];
        // resetto la media
        for (int j=0;j<5;j++)
            media[j] = 0.0 ;

        // calcolo la media
        for (int i=0;i<dg1->buffersize;i++)
        {
            for (int j=0;j<5;j++)
                media[j]+=(float)dg1->buff[5*i+j];
        }
```

```
      for (int i=0;i<5;i++)
            media[i] = (media[i]/dg1->buffersize);

      if (dg1->SelfCalibration)
      {
            for (int i=0;i<5;i++)
            {
                  if (media[i]<dg1->fmin[i])
                        dg1->fmin[i] = (int) media[i];
                  if (media[i]>dg1->fmax[i])
                        dg1->fmax[i] = (int) media[i];
            }
      }
            for (int i=0;i<5;i++){
            f[i]  =  (float)100.0*(media[i]-dg1->fmin[i])/(dg1->fmax[i]-
dg1->fmin[i]);
//          f[0] for thumb and so on till litle finger.

            //printf(" value of bend in finger f:%4d \n",f[i]);

            }


return f;
}
int main(int argc, char* argv[])
{

/*Initialize COM library for Sensor */
      printf("Initialize COM library...");
      if (CoInitialize(NULL) != S_OK)
            printf("Failed to initialize COM library");
      else
            printf("done\n\n");

      /*Create filter instance and set filter parameters for Sensor*/
      SetupFilter();
```

```
    /* OpenGL Calls */



  glutInit(&argc, argv);
  glutInitDisplayMode(GLUT_DOUBLE | GLUT_RGB | GLUT_DEPTH);
  main_window=glutCreateWindow("shadow_virtaul arm");
  glutInitWindowSize (840, 500);
  glutInitWindowPosition (150, 150);
  //glutKeyboardFunc(keypress);
  glutDisplayFunc(Robot_Display);
  //glutIdleFunc(idle);
  glutReshapeFunc(reshape);
  //console_read();


GLUI *glui = GLUI_Master.create_glui( "GLUI" );
  new GLUI_Checkbox( glui, "Wireframe", &wireframe );
  (new GLUI_Spinner( glui, "Segments:", &segments ))
    ->set_int_limits( 3, 60 );

  glui->set_main_gfx_window( main_window );

  /* We register the idle callback with GLUI, *not* with GLUT */
  GLUI_Master.set_glutIdleFunc(idle);



    // Start processing by MotionTracker object
    printf("Start processing by the MotionTracker object..");
    pMT->MT_StartProcess();
    printf("done\n\n");



proj = new Project();
gloveid1 = proj->AddDataGlove("dataglove1",10,0);
```

```
proj->StartSampling(1);



glutMainLoop();




        // Stop processing by MotionTracker object
        printf("Stopping filter...");
        pMT->MT_StopProcess();
        printf("done\n\n");

        // Release and clean up MotionTracker object
        printf("Release MotionTracker object...");
        if (pMT != NULL)
        {
                pMT->Release();

                pMT = NULL;

                printf("done\n\n");
        }

        // Uninitialize COM library
        printf("Uninitialize COM library...");
        CoUninitialize();
        printf("done\n\n");

        return 0;

}
```

APPENDIX 2

System Evaluation Questionnaires

Instructions: Please tick/circle one option in the questions below in order to give us an insight of your experience with our VR-based Upper Extremity Stroke Rehabilitation System

1. Over all I am satisfied with how easy it is to use the VR system

Strongly Agree	1	2	3	4	5	6	7	Strongly Disagree

2. It was simple to use the VR system

Strongly Agree	1	2	3	4	5	6	7	Strongly Disagree

3. I could effectively complete the task and scenarios using this VR system

Strongly Agree	1	2	3	4	5	6	7	Strongly Disagree

4. It was easy to learn to use this VR system

Strongly Agree	1	2	3	4	5	6	7	Strongly Disagree

5. The VR system was fun and engaging

Strongly Agree	1	2	3	4	5	6	7	Strongly Disagree

6. How mentally demanding was the task

Very Low	1	2	3	4	5	6	7	Very High

7. How physically demanding was the task

Very Low	1	2	3	4	5	6	7	Very High

PUBLICATIONS

Prashun, P., Hadley, G., Gatzidis, C., "*Developing a Virtual Reality Stroke Rehabilitation Prototype*", 13th International Conference on Human Computer Interaction, Springer, San Diego, California, US, 19-24 July, 746-750, (2009). ISBN: 978-3-642-02884-7.

Prashun, P., Hadley, G., Gatzidis, C., "*Investigating the Trend of Virtual Reality-based Stroke Rehabilitation Systems*", 14th International Conference Information Visualisation, London, United Kingdom, 26-29 July, 641-647, (2010). ISBN: 978-0-7695-4165-5