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A comparative analysis of haptic and EEG devices for evaluation and training of post-stroke patients within a virtual environment

Gregory Nicholas Ranky
New Jersey Institute of Technology

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ABSTRACT

A COMPARATIVE ANALYSIS OF HAPTIC AND EEG DEVICES FOR EVALUATION AND TRAINING OF POST-STROKE PATIENTS WITHIN A VIRTUAL ENVIRONMENT

by
Gregory Nicholas Ranky

Virtual Rehabilitation benefits from the usage of interfaces other than the mouse and keyboard, but also possess disadvantages: haptic peripherals can utilize the subject's hand to provide position information or joint angles, and allow direct training for specific movements; but can also place unneeded strain on the limbs; brain-machine interfaces (BMI) can provide direct connections from the user to external hardware or software, but are currently inaccurate for the full diversity of user movements in daily life and require invasive surgery to implement. A compromise between these two extremes is a BMI that can be adapted to specific users, can function with a wide range of hardware and software, and is both noninvasive and convenient to wear for extended periods of time.

A suitable BMI using Electroencephalography (EEG) input, known as the Emotiv EPOC^{TM} by Emotiv Systems was evaluated using multiple input specializations and tested with an external robotic arm to determine if it was suitable for control of peripherals. Users were given a preset periodicity to follow in order to evaluate their ability to translate specific facial movements into commands as well as their responsiveness to change the robot arm's direction. Within 2 weeks of training, they maintained or improved axial control of the robot arm, and reduced their overall performance time. Although the EPOC^{TM} does require further testing and development, its adaptability to multiple software programs, users and peripherals allows it to serve both Virtual Rehabilitation and device control in the immediate future.

A COMPARATIVE ANALYSIS OF HAPTIC AND EEG DEVICES FOR EVALUATION AND TRAINING OF POST-STROKE PATIENTS WITHIN A VIRTUAL ENVIRONMENT

by
Gregory Nicholas Ranky

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APPROVAL PAGE

A COMPARATIVE ANALYSIS OF HAPTIC AND EEG DEVICES FOR EVALUATION AND TRAINING OF POST-STROKE PATIENTS WITHIN A VIRTUAL ENVIRONMENT

Gregory Nicholas Ranky

12.8.09

Dr. Sergei Adamovich, Thesis Advisor — Date
Associate Professor of Biomedical Engineering, NJIT

12/8/09

Dr. Richard A Foulds, Committee Member — Date
Associate Professor of Biomedical Engineering, NJIT

12/8/09

Dr. Mesut Sahin, Committee Member — Date
Associate Professor of Biomedical Engineering, NJIT

BIOGRAPHICAL SKETCH

Author: Gregory Nicholas Ranky

Degree: Master of Science

Date: January 2010

Undergraduate and Graduate Education:

- Master of Science in Biomedical Engineering,
  New Jersey Institute of Technology, Newark, NJ, 2010
- Bachelor of Science in Biomedical Engineering,
  New Jersey Institute of Technology, Newark, NJ, 2005

Major: Biomedical Engineering

Presentations and Publications:

Gregory N. Ranky, (2007) "Mobile robot sensor and networking design to enable cooperative behavior," *Industrial Robot: An International Journal, Vol. 34, issue 1.*, 21-25.

Gregory N. Ranky and Paul G. Ranky, (2005) "Japanese prototype service robot R&D trends and examples," *Industrial Robot: An International Journal, Vol. 32, issue 6.*, 460-464.

Many engineers and designers have claimed to be influenced by speculative fiction during their youth, from the design of submarines from the Nautilus of Jules Verne to the creation of cellular phones from the tricorders of Star Trek. Had I been told 20 years ago that I would be working with translating electrical signals from the brain to play games or move robots, I would almost have certainly considered it fiction, and would have jumped at the opportunity to explore it had I known it would happen.

Brain-machine interfaces and brain-computer interfaces are an extension of the developments in computing and neuroscience, but they're also part of something more fundamental: the development of consciousness. Although tool use is cited as the main distinction between humans and other organisms, the use of non-bodily implements by birds and primates removes this distinction. The computer scientist and science fiction author Vernor Vinge said that humans are distinguished not by tool use but by 'the outsourcing of consciousness to the environment'. Historically, we have used books, paintings, photographs, audio and video to extend our memory, telescopes and microscopes to extend our eyes and ears, and the internet to extend our minds.

Doing so has allowed humanity as a species to learn and change individually and in groups continuously within a lifetime. As Marshall McLuhan predicted, we now wear all mankind as our skin, and the process continues with BMIs, prosthetics, robotics and A.I. development. Improving the connections between the biological and non-biological consciousness of the present and future is therefore imperative not only for survival but increased prosperity.

The creation of new technologies also carries new laws and regulations to determine its use, as well as the consequences for its misuse. But legality has historically been slow to catch up to ethics, which runs adjacent to laws and exists within the places and times where laws do not yet cover.

I don't see any incompatibility between science and ethics, because to me ethics is a science as well; specifically the science of consequences, the effects of one's assumptions, goals and actions on oneself, other beings, and the environment. As the spread of information and computing technologies extends deeper into our homes, our businesses and our bodies it is necessary for those researching and developing them to pursue their creative and ethical application for environmental well-being and human health, happiness and peace of mind.

Within the next century, the merging between humans and their artifacts will continue at a pace faster than any century before, and by its end our species will have new and unusual aides, assistants and partners to live and work with. Our task for our artifacts and infrastructure is to give them a sense of social awareness, ethics and the ability to learn, making them not simply more like us, but moral like us. In return, we shall extend our consciousness through our environment and recreate ourselves to be more insightful, compassionate, creative and optimistic.

I've no doubt that we'll have challenges we hadn't expected or prepared for yet, but I remain optimistic. Because whilst we may not have the best solution the first time, that doesn't have to prevent us from creating one in time.

ACKNOWLEDGMENT

I'd like to thank all those who assisted, sponsored and inspired me during the research within this thesis. Dr. Adamovich and Dr. Foulds have my gratitude for their patience and willingness to experiment with new technologies and their valuable insight and feedback. I'd also like to thank them, and Dr. Sahin as well for accepting my request to be on my Committee in order to evaluate my work.

I'm grateful to the NJIT BME Department for accepting me and funding my research, and I'm glad to contribute my knowledge and skills to furthering human health and welfare, both now and in my future studies here.

Diego Ramirez, thank you for working with me on the iARM, I know I couldn't have finished what I did without your help.

Qinyin Qiu and Gerard Fluet, thank you both for your time and enthusiasm, and listening to what I have to say even if I didn't understand everything I was doing initially.

All those who volunteered for testing and experimentation with the headset even if they haven't yet participated yet; I appreciate your enthusiasm and curiosity, two elements essential to innovation and discovery.

I'd also like to thank my family for their unending patience, openness, support and understanding. My dad, who showed me that those who innovate and create wealth are those who build a better future, my mum who taught me to respect the complexity and interconnectedness of life and health, and my brother Richard for proving that you don't have to have the same goal to travel in the same direction.

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LIST OF SYMBOLS

X	Y
API	Application Programming Interface
BCI	Brain Computer Interface
BMI	Brain Machine Interface
EEG	Electroencephalography
EMG	Electromyography
EML	EmoComposer Markup Language
ERT	Extended-Range Transmitter
fMRI	Functional Magnetic Resonance Imaging

CHAPTER 1

INTRODUCTION

1.1 Objective

The objective of this thesis is to evaluate the usage of a recent EEG-based Brain-Machine Interface, and compare its accuracy and versatility to existing nonstandard computing interface peripherals used for Virtual Rehabilitation.

For the virtual hand training, the CyberGlove® was used with position sensing for two post-stroke patients, who trained over a period of 2 weeks using two programs that monitored and scaled with their progress.

For the EEG, the Emotiv EPOC^{TM} headset by Emotiv Systems, Inc. was used, with given input Suites evaluated for their effectiveness for users, and the most efficient Suite used to conduct training conducted using direct neural sensing to send keyboard input to control a robotic arm, the iARM by Exact Dynamics. Two users without any neurological disorders were then trained to match periodicity in each of 4 Axis Tests which gauged their ability to periodically change between directions in fixed intervals over a set time, repeated over a 2 week period.

1.2 Problem Statement

Rehabilitation is one of the fastest growing fields in medical research. As humans live for greater lengths of time, the desire for improved quality of life as well as increased lifespans becomes essential. And in the events of accidents or injuries, rehabilitation allows those affected to live fuller, more productive lives.

Because of the time and training needed to educate physical therapists, the varying requirements for patient-specific programs and the need for consistent training, it becomes difficult to provide patients with the optimal care that they require. Furthermore, due to the limited number of physical therapists and the need to maintain safety and hygiene standards, they are usually limited to hospital areas, decreasing the frequency of patient visitations in a given space or time.

Virtual Rehabilitation provides both portability due to the ease of transference for software, consistency in training and measuring results, and customizability to a patient's skill level.

However, a primary concern in Virtual Rehabilitation is the relevance of the exercises performed to the activities of daily life. Becoming competent or skilled at a simulation is rewarding for the designer or for the patient, but the primary goal of Virtual Rehabilitation is to allow the user to translate and apply the skills acquired through training to his or her habits and lifestyle.

1.3. Background Information

VR Rehabilitation involves the use of a combination of hardware and software to improve a subject's reflexes, speed, coordination, and/or spatial awareness. Their primary advantages lie in repeatability and safety, as a program can be configured for a specific number of tests per subject, and can adapt its difficulty level depending on regular progress, as well as record and organize data obtained during trials. This allows consistency in conducting trials, as well as the generation of environments that would be difficult or costly to perform physically. In terms of safety, movement of objects and manipulation of the environment occurs primarily within software, avoiding possible damage to equipment or injury to the participants caused by mishandling or dropping objects. Therapeutic uses have also been developed to allow patients to overcome specific fears or long-term treatments through repeated interaction or immersion (Haik, 2006).

Although software can be configured to function on commercial PCs and laptops due to continuous improvements in electronics, the need to perform specific movements means that using a mouse, touchpad or keyboard is limiting and potentially difficult for the patient. Simultaneously, users should refrain from performing actions that would place further strain on their bodies, especially if they have received severe injuries.

This research will therefore compare the ease of usage, training time, and relevance to daily activities of both a Medical Haptic Computer Interface and a Commercial EEG headset.

1.3.1 Medical Haptic Computer Interfaces and Training Tools

Virtual Rehabilitation can be classified either by patient population or device type; the former category distinguishes specific needs for patients such as Musculo-skeletal/orthopedic Rehabilitation for those with bone or muscle injuries, and Post-Stroke Rehabilitation for those who have suffered paralysis to one side of their body due to a neural hemorrhage (Burdea, 2003).

In order to regain fine motor control, repeatable, safe training activities are needed; and interfaces which can make use of alternate modes of input or movement are part of this process. Haptic devices use interactions with a subject's hand to control a virtual equivalent through joint sensing, or to impart force on specific locations. This allows a more immersive and direct form of movement than would be provided by a mouse or keyboard.

Figure 1.1 An example of Virtual Rehabilitation. In a simulated peg-board exercise, the user wears a haptic glove that translates his hand position and finger joint angles to an equivalent hand on screen. This can be repeated with precise starting positions for the pegs, and avoids loss or damage of equipment if physical pegs were used. As the glove does not offer tactile feedback, the user has to rely primarily on sight to determine exact positions.

Source: Broeren, J., Rydmark, M., Björkdahl, A., Sunnerhagen, K.S., (2007). Assessment and Training in a 3-Dimensional Virtual Environment With Haptics: A Report on 5 Cases of Motor Rehabilitation in the Chronic Stage After Stroke. *Neurorehabilitation and Neural Repair, 21*. 180-189.

Haptic devices can also be used for those who have diminished or absent vision, as the equivalent neural processing space is more readily available for the remaining senses (Tzovaras, 2004). This remains a difficulty due to the sensitivity needed for approximating human touch accurately, leaving current devices with contact points that are few in number and low resolution.

Robot usage in rehabilitation can also incorporate haptic components to allow semi-autonomous practice and personalized assistance (Jack, 2001), (Veras, 2008). BCIs and BMIs that work in these roles can have a greater emphasis on safety and accuracy instead of velocity or force generation, specifically if they are used by those with motor or neural disabilities such as hemiparetic stroke (Broeren, 2007), (Wolpaw, 2002).

1.3.2 Prior Research on Using EEG as an Interface or Controller Scheme

Regardless of where conscious motor control is executing in the body, the planning, processing and memorization begins in the brain. The development and usage of brain-machine interfaces (BMIs) and brain-computer interfaces (BCIs) has focused on improving resolution and speed whilst minimizing health risks and user training times, regardless of the method used. Electroencephalography (EEG) has meets all of the above criteria effectively, allowing for the greatest range of users and rehabilitation scenarios.

EEG functions by recording the electrical activity of neurons in the brain by placing electrodes over a patient's scalp (Calhoun, 2008). Because electrode placement is external, there is no need for invasive surgery or implants that would otherwise interfere with brain function, or corrode and release fragments and material by-products into the blood. Unlike fMRI, no dyes or injections are needed to improve signal resolution, and no ionizing radiation or external applied magnetic fields are involved. Out of the existing neural measurement methods, EEG also has the greatest temporal resolution, usually on the order of milliseconds instead of seconds for fMRI. This direct monitoring also allows measurements in subjects with limited motor response either due to injury or fatigue. However, because EEG functions by measuring the integration of all outgoing signals for neurons instead of initial action potentials (Cincotti, 2008). Therefore, it trades specificity for speed, and the primary disadvantage however, is a lower spatial resolution compared to fMRI and the need to prepare a subject's scalp to improve conductivity, usually by abrading the surface to remove dead cells and applying conductive gel to the electrodes (Kostov, 2000).

EEG is also fundamentally a sensory application, and cannot directly alter brain activity, which Transcranial magnetic stimulation (TMS) is able to do. Whilst this may seem initially to be a disadvantage, it avoids any risks associated with interference, such as the possibility of seizures in the usage of TMS. This allows the user to utilize EEG-based interfaces without risk or fear of injury or side effects. EEG also has the advantage of a type of biofeedback not usually found in traditional rehabilitation, specifically the user's own neural activity, which can be used to engage their attention and provide them with additional cues for learning (Liu, 2005). Cue-based BCIs allow new subjects to more easily acclimate to unfamiliar technologies, thereby improving accuracy and reducing errors (Vidaurre, 2006).

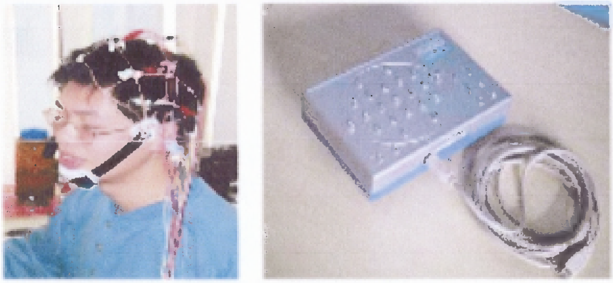


Figure 1.2 An EEG-based biofeedback system using 29 electrodes, which collects raw EEG data and sends it via a USB port to be displayed on a PC.

Source: Liu, M., Wang, J., Yan, N., & Yang, Q. (2005). Development of EEG Biofeedback System Based on Virtual Reality Environment. *Proceedings of the 2005 IEEE Engineering in Medicine and Biology 27th Annual Conference, Shanghai, China September 1-4, 2005.*

EEG data also needs to be filtered by software to remove signals not associated with brain activity, including heart rate, eye movements, voluntary muscle activity, and noise from surrounding electronic equipment (Shao, 2008). These can be removed reliably through software due to frequency ranges during specific states of rest or activity, and by positioning electrodes as close to the scalp surface as possible. EEG data can also be integrated to update simulations or models based on continuous user performance, such as movement through a virtual environment or increasing the level of difficulty in a training exercise to match increases in duration and skill (Leeb, 2007).

CHAPTER 2

CYBERGLOVE VIRTUAL TRAINING FOR HEMIPARETIC STROKE

2.1 Chapter Introduction

Haptic peripherals allow greater range of movement within a virtual environment compared to a mouse due to direct correspondence of user movements, allowing navigation in 3 dimensions.

In order to determine the effectiveness of a commercial EEG-based control scheme, an evaluation of the strengths and weaknesses of an existing commercial haptic sensory peripheral is needed.

2.2 Device Description

The CyberGlove® is an input peripheral designed to translate the overall position and finger orientations of a user's hand into a virtual hand model. This allows for Virtual Rehabilitation and the training of hand movements within a consistent environment. The CyberGlove® communicates with a PC using a Flock of Birds® Motion Tracker, using a pulsed DC magnetic field to track movement. This allows a wider range of environments than AC trackers, and avoids the need for a clear line-of-sight between the CyberGlove® and the Flock of Birds®.

Figure 2.1 The CyberGlove®, when unworn.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

Figure 2.2 The CyberGlove® when worn on the right hand. The position sensor is attached to the top of the wrist using a Velcro pad. Because this is the only location it is attached to, it becomes inconvenient for the user, as it hangs below the attachment site and risks becoming entangled.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

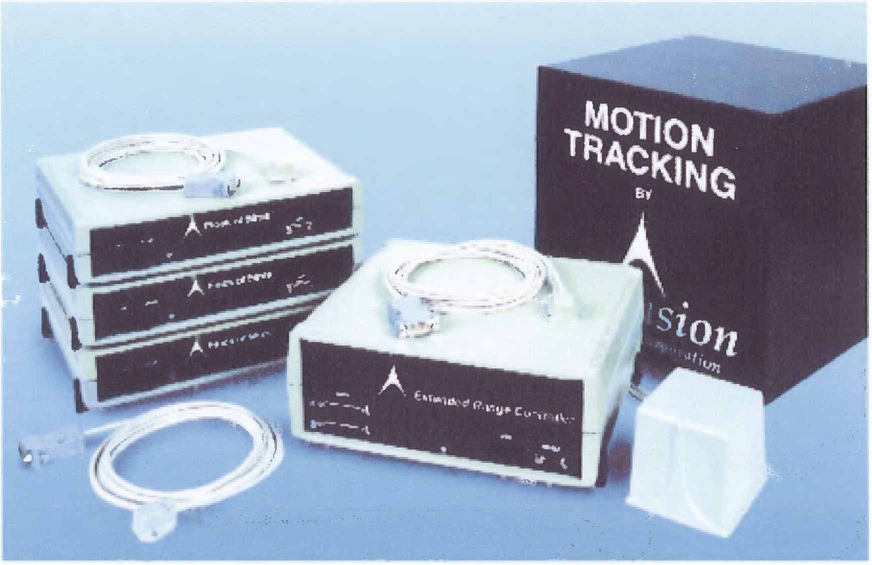


Figure 2.3 The Flock of Birds® Motion Tracker is displayed here, a single section of the leftmost stack was utilized for the VR training described below.

Source: Ascension Technology Corporation http://www.est-kl.com/fileadmin/media/pdf/Ascension/Flock_of_Birds.pdf, accessed November 20, 2009.

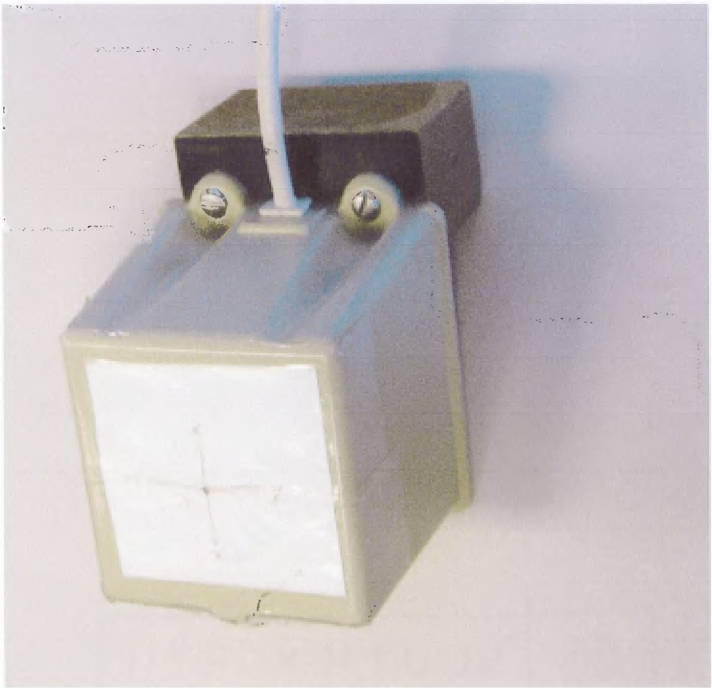


Figure 2.4 The Flock of Birds® Extended-Range Transmitter (ERT) is shown here, the label is to remind the users and experimenters of the orientation of the CyberGlove in a virtual environment.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

Figures 2.1 to 2.2 show the CyberGlove® unused and worn respectively. Figure 2.3 shows a selection of Flock of Birds® Motion Trackers, with a sample of the leftmost stack used in this experiment, and Figure 2.4 shows the Extended-Range Transmitter with an attached label to denote corresponding orientations within a virtual environment.

Using a virtual environment which is interacted with using hand movements provides training for hand-eye coordination without risk of injury from lifting or dropping loads. For those who have suffered hemiplegic stroke, this allows improved motor control in a controlled and engaging environment, using simulations such as piano key sequences and grasping objects (Merians, 2006).

The training used with the CyberGlove® in this experiment consisted of 3 hours of training per patient, 4 days per week over a period of 2 weeks. During this time, both patients spent 1.5 hours of each 3-hour session on training using a CyberGlove® in 2 separate programs. The first CyberGlove® program consisted of a simulation of a piano keyboard. In this program, a series of keys would light up in sequence, and the user had to move a virtual hand horizontally and press the required key with the highlighted finger. The second CyberGlove® program consisted of a virtual three dimensional garden, with a fountain located in the center. The goal is this simulation was for the user to grasp a hummingbird which appeared at random positions, and then place it on top of the fountain 30 times within each trial. These are shown below in Figures 2.5-2.8.

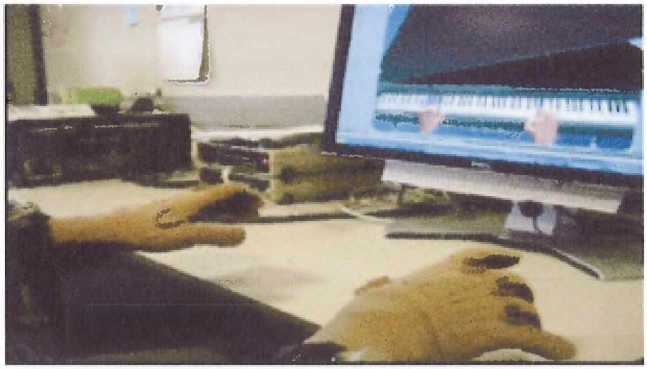


Figure 2.5 An example of Piano Training using the CyberGlove®, the subjects in this experiment used one hand exclusively instead of both simultaneously.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

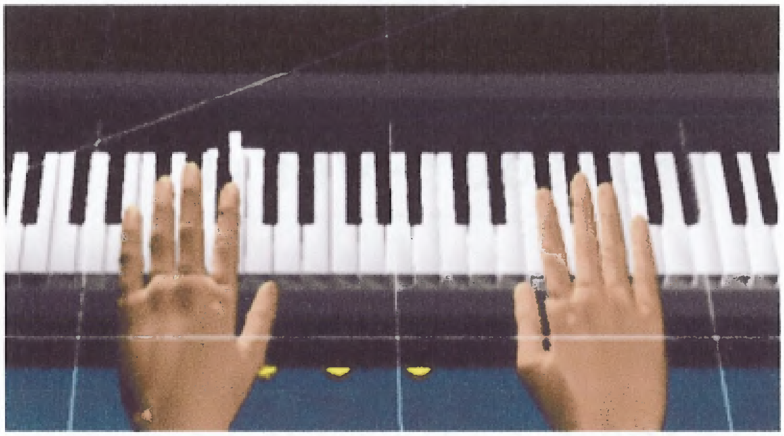


Figure 2.6 An image of the virtual hands in the Piano Training. In this experiment, both subjects had only one hand visible. The virtual hand maintains its orientation regardless of the orientation of the CyberGlove®, and can only move in the horizontal plane. The fingering and the corresponding key in each trial is highlighted in blue on the virtual hand.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

Figure 2.7 An image of the Hummingbird reach and grasp. The bird itself has a fixed location, but reappears in a different location once it has been grasped and placed on the fountain. Due to the lack of shadows, depth perception of the Hummingbird can be difficult.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

2.3 Data Section

The trials conducted involved two subjects, each with hemiplegic stroke on one side of their body, their information is given below in Table 2.1.

Table 2.1 Subject Information for Virtual Piano and Hummingbird Trials

Subject Initials	**Gender**	**Handedness Pre-Stroke**	**Hemiplegic Stroke Side**
JC	Male	Right	Right
MAB	Female	Left	Left

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

Their progress in both the Piano keyboard and the Hummingbird Grasp is shown in Tables 2.2 and 2.3 respectively. Each of the given values of duration for Hummingbird Grasp trials, piano fractionation angle and piano accuracy are the mean within all the trials within each daily session for two consecutive days. The first mean is for all the trials within the first 2 days of trials for the subject, and the second mean is for all the trials within the last 2 days of trials for the subject.

Table 2.2 Subject Means for Virtual Piano Trials

Subject Initials	**Piano Fractionation 1 (°)**	**Piano Fractionation 2 (°)**	**Piano Accuracy 1 (%)**	**Piano Accuracy 2 (%)**	**Piano Duration 1 (s)**	**Piano Duration 2 (s)**
JC	0.0443	0.1930	41.67	22.55	7.48	4.60
MAB	0.2719	0.5580	57.29	52.98	1.75	2.88

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

Table 2.3 Subject Means for Virtual Hummingbird Trials

Subject Initials	**Hummingbird Duration 1 (s)**	**Hummingbird Duration 2 (s)**
JC	24.02	10.65
MAB	24.43	12.23

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

2.4 Analysis of Data

When seeing the results of the Piano and Hummingbird Trials, there is a general improvement shown by increase in Piano Fractionation Angle and decrease in Piano Duration and Hummingbird Duration, though the Piano Accuracy Percentage decreased.

The increase in the mean Piano Fractionation angle for both subjects revealed that they were able to move the necessary fingers at a greater range to press the required keys. The decrease in Piano Accuracy in both subjects may be due to an attempt to decrease overall trial speed, and would likely come from moving other fingers concurrently with the required finger, although subject MAB had a significantly smaller decrease in accuracy. The decrease in Piano Duration reveals an increased familiarity with the software and controls, although subject MAB has an increase in this value; combined with the lower decrease in accuracy, this would likely be due to attempting to improve accuracy, which would require more time. The decrease in Hummingbird Duration in both subjects indicates increased familiarity and accuracy in determining the Hummingbird's location and grasping it quickly.

2.5 Limitations and Opportunities for Improvement

Whilst the CyberGlove® has shown to be viable for Virtual Rehabilitation due to its robust, compact design, there remain opportunities for improvement for future peripherals.

Firstly, the glove itself must be physically tethered to a motion tracker box that filters and processes position and joint bending data for the training software. This becomes highly limiting when changing hands between the subjects, and made more difficult for those who have limited motor control during testing. It was also found that during CyberGlove® training in both the Piano and Hummingbird simulations, both of the patients held their hands suspended in midair. Both of them were visibly tired once each session was complete, which can be more produced in older subjects as well. In addition, the CyberGlove® maintains the same orientation with the palm facing down regardless of the user's hand position. Whilst this provides consistency and avoids unintentional movements resulting from improper grip or oversensitivity in motion, it greatly limits future potential training regimes by not allowing for the possibility of changes in orientation.

Also, the sensors that transmit the position of the CyberGlove® are connected to the glove by a Velcro tab. Whilst this allows for fast adjustment, it also causes the sensor to migrate depending on the usage duration.

Consistency in positioning can also be difficult, as the relative position between the Flock of Birds®, the ERT and the CyberGlove® changes not only when the glove is moved, but also when the ERT has shifted position. Although the position of the box can be marked, its placement becomes limited if surrounding objects are added to the workspace. The label on the ERT shown in Figure 2.4 is due to the lack of immediate markers for the subject to determine which axis corresponds to xyz movement. If a peripheral can connect directly to a desktop or laptop computer without a secondary receiver, then maintaining a consistent starting position becomes easier for the user. The Flock of Birds® itself also covers a 24cmx29cm area, which increases clutter and limits its usage in confined spaces or mobile applications.

Cost is also an important consideration; when first released in 1996, a CyberGlove® cost an estimated $9800, which in 2009, would prohibit its use by private individuals, and limit its access by clinicians, medical facilities and academic institutions. An updated version, the CyberGlove II does not have a price listed as of October 2009, but addresses the issue of mobility by having wireless access via a USB port. Power supply is provided by a 3-hour battery, which is useful, but significantly lower than other mobile devices such as cellphones and PDAs.

From the above data, it becomes apparent that haptic devices, whilst useful for virtual hand training and improved hand-eye coordination, cannot cover all possible forms of user input or peripheral control. As there are currently no widely available output devices that precisely replicate the speed, dexterity, tactile feedback and range of movement of a human hand, a direct correspondence to finger movement is also currently unnecessary for output to a device's movement. Therefore, an EEG-based input device can be used where repetitive hand movements are straining, when hands are needed to be unencumbered, or when the subject is limited in the use of his or her limbs.

CHAPTER 3

EMOTIV EPOC OVERIEW AND INPUT SUITE EVALUATION

3.1 Overview of the Emotiv EPOC EEG Headset

The Emotiv EPOC^{TM} EEG Headset is an input peripheral released in September 2009. Created by Emotiv Systems in conjunction with the IDEO Design group, it was originally designed for use as a means of providing input to games by EEG signals. Using a series of 16 electrodes, the EPOC^{TM} can measure conscious thoughts, levels of attention and facial expressions to control electronic or physical devices. The Emotiv detection results are translated into software structures called EmoStates^{TM} which are used by the Emotiv Application Programming Interface (API). Because the EPOC^{TM} uses EEG as its signal input, it obtains the greatest speed out of existing brain activity measurement methods; and being noninvasive, greatly improves hygiene, removes the need for surgery, and allows for a greater number of users within a given training period. At a developer price of $299, it is the first EEG designed for public usage and end-user customization, and is significantly less expensive than prior EEG systems. Whilst the number of electrodes is comparable to a standard medical EEG system, which uses 16-25 electrodes, the EPOC^{TM} does not require a moistened cap to improve conduction. This is because each electrode rests on the skull with an individual, removable moistened felt pad, allowing each reading to be individually adjusted and reducing the need to remove scalp hair, which discourages patients from regular readings and which requires the user to remain still during the procedure. The sampling rate is also comparable to existing EEG devices used for Virtual Rehabilitation, with an internal sampling rate of 2048Hz, whilst a recent medical equivalent samples at 1000Hz (Lin, 2007).

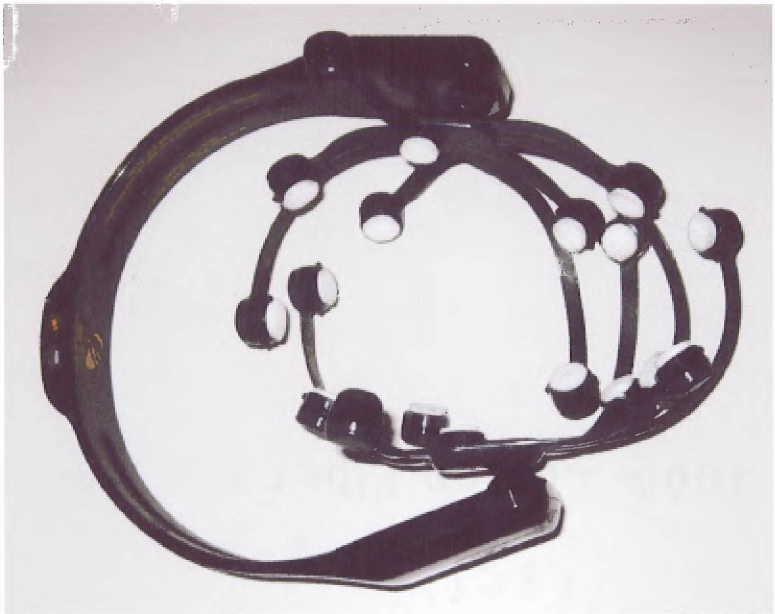


Figure 3.1 The Emotiv EPOC^{TM} seen from below and from the side; the front is facing to the right.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

Figure 3.2 The Emotiv EPOC seen from the side, with the front facing to the right. The black pads are nonconductive Reference Electrodes, which are placed just behind the user's ears and are used to position the headset consistently.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

Figure 3.3 The wireless USB connector, power toggle switch and charging socket of the Emotiv EPOC^{TM} are shown here. The toggle switch is currently in the 'off' position, whilst sliding it to the USB icon is 'on'.

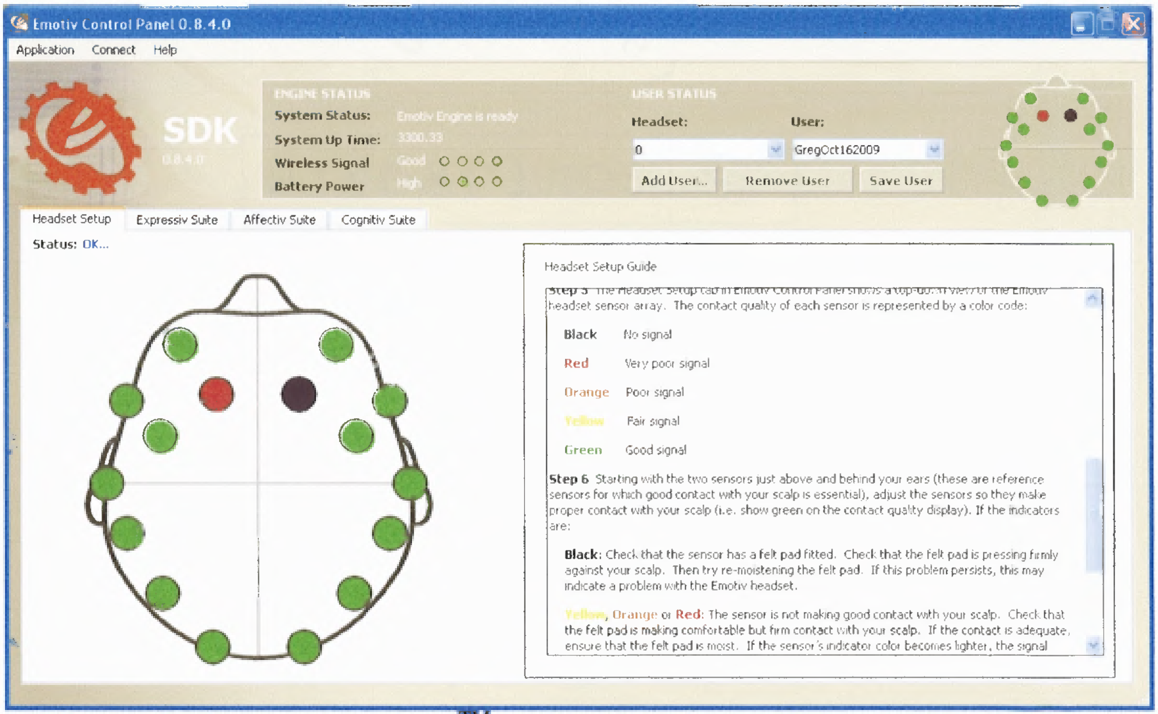
Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

Figures 3.1-3.3 show the EPOC^{TM} headset and wireless USB connector. When not worn, the headset is 17cm at its widest point and 20cm long from the endmost electrodes to the rear brace. The brace itself is 3.7cm at its thickest point, and the distance between the reference electrodes and the uppermost receiver electrodes is 10cm. Each of the connecting arches are flexible in a single direction, allowing them to adjust around an adult or adolescent head to allow accurate positioning. Combined with its negligible mass, it can be carried and stored in a rigid or flexible container.

Unlike current EEG devices, the EPOC^{TM} follows the trend of electronics and computing peripherals by using a wireless USB receiver, connected to the desktop or laptop with the receiver software, with an approximate range of 3 meters without signal loss. This frees the user or those monitoring training from accidentally falling and damaging the hardware, whilst providing greater mobility than prior EEG systems which require multiple cables connected to a computer.

In terms of cost, it is far more affordable for public and academic research, with the emulator and primary software available for free, and the Headset itself currently retailing at $299. Whilst this seems comparable to existing medical EEG devices, the EPOC^{TM} is self-contained, with internal reception, decoding and amplification performed by the headset and set to a wireless USB receiver. In comparison, a medical EEG requires not only the electrodes, but input cables, disposable cup electrodes and decoder box, raising the total price to approximately $970. Accompanying software can be purchased for the EPOC^{TM} which allows direct display of EEG data at a greater cost than the Developer price, ranging from $1,000 to $3,000. The assumption for this given price is that medical research sites and clinics would be the customers primarily interested in direct EEG data, and would consider the equivalent cost of an EEG device to be comparable. Finally, a lithium battery provides 12 hours of power with a charge time of 100 minutes, allowing it to be used for a continuous workday or for sequential daily sessions.

The complete software consists of 3 separate programs: EmoComposer^{TM}, EmoKey^{TM} and Emotiv Control Panel^{TM}. EmoComposer^{TM} functions as an emulator for the Emotiv EmoEngine^{TM}, and can send user-defined EmoStates^{TM} to any software which uses the Emotiv API, including EmoKey^{TM} and Emotiv Control Panel^{TM}. EmoKey^{TM} can be configured to send keystrokes to an active program when specific conditions are met, and can accept EmoStates^{TM} from EmoComposer^{TM} or Emotiv Control Panel^{TM}. Emotiv Control Panel^{TM} receives input from an EPOC^{TM} headset, and can supply real-time training programs to customize input for different users. Each of the Programs is shown below in Figures 3.4-3.6.



ENGINE STATUS

System Status: Emotiv Engine is ready

System Up Time: 3300.33

Wireless Signal Good ○ ○ ○ ○

Battery Power High ○ ○ ○ ○

USER STATUS

Headset: 0

User: GregOct162009

Status: OK...

Headset Setup Guide

Step 5 The Headset Setup tab in Emotiv Control Panel shows a top-down view of the Emotiv headset sensor array. The contact quality of each sensor is represented by a color code:

Black	No signal
Red	Very poor signal
Orange	Poor signal
Yellow	Fair signal
Green	Good signal

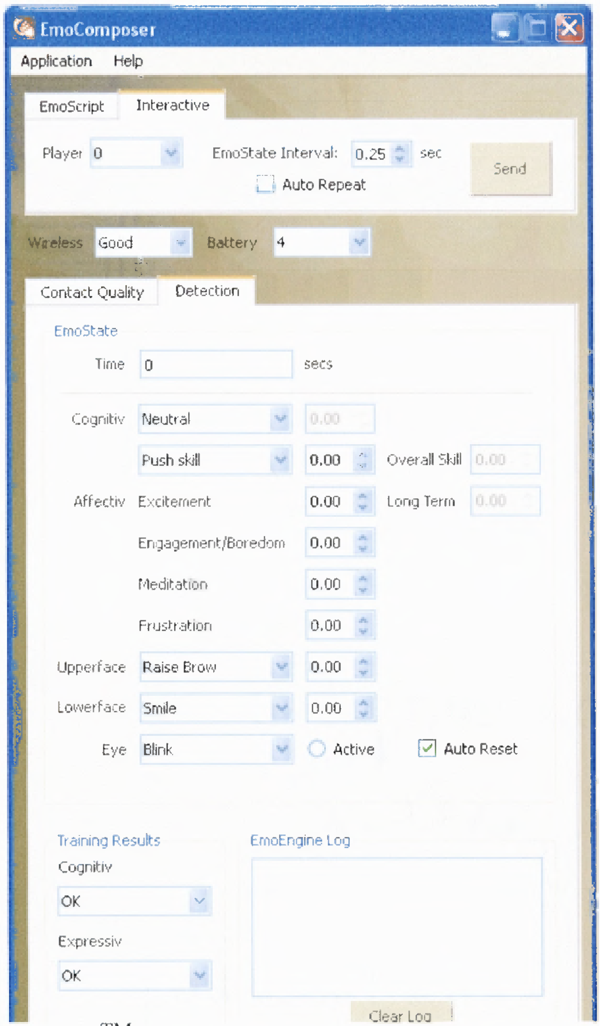
Step 6 Starting with the two sensors just above and behind your ears (these are reference sensors for which good contact with your scalp is essential), adjust the sensors so they make proper contact with your scalp (i.e. show green on the contact quality display). If the indicators are:

Black: Check that the sensor has a felt pad fitted. Check that the felt pad is pressing firmly against your scalp. Then try re-moistening the felt pad. If this problem persists, this may indicate a problem with the Emotiv headset.

Yellow, Orange or **Red:** The sensor is not making good contact with your scalp. Check that the felt pad is making comfortable but firm contact with your scalp. If the contact is adequate, ensure that the felt pad is moist. If the sensor's indicator color becomes lighter, the signal

Figure 3.4 Emotiv Control Panel™; this program receives direct EEG input from the user, and contains the 3 input suites accessed by the respective tabs, and gives instructions for positioning the EPOC™ on the user's head and obtaining the highest conduction quality. The Headset Number is given in binary, so '0' would mean the first acknowledged headset. Battery life and electrode signal quality are indicated on the top, regardless of Suite. A user, whether previous or new, must always be selected in order to use this program.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.



Player 0

EmoState Interval: 0.25 sec

☐ Auto Repeat

Wireless Good

Battery 4

Time 0 secs

Cognitiv Neutral 0.00

Push skill 0.00

Overall Skill 0.00

Affectiv Excitement 0.00

Long Term 0.00

Engagement/Boredom 0.00

Meditation 0.00

Frustration 0.00

Upperface Raise Brow 0.00

Lowerface Smile 0.00

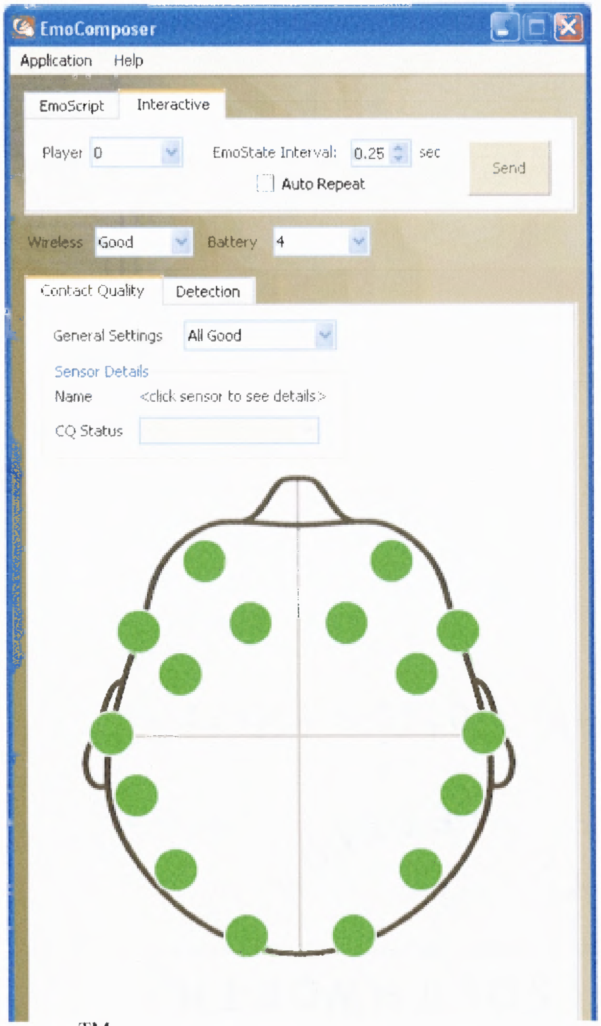
Eye Blink ○ Active ☑ Auto Reset

Cognitiv OK

Expressiv OK

Figure 3.5 EmoComposer^{TM} is shown here; this program is used to run a preset sequence of Suite inputs with a given signal quality. When connected to EmoKey^{TM}, it will send the commands to the selected Mapping, which in turn will convert them into keystrokes when the selected conditions are met.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.



Player 0

EmoState Interval: 0.25 sec

☐ Auto Repeat

Wireless Good

Battery 4

General Settings All Good

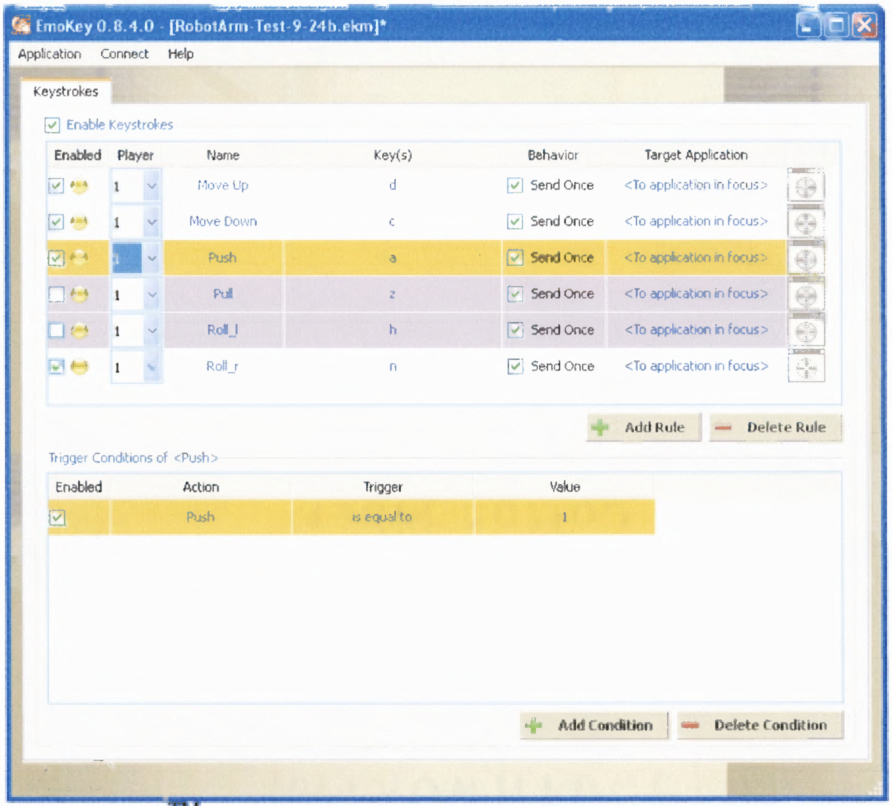
Sensor Details

Name <click sensor to see details>

CQ Status

Figure 3.6 EmoComposer^{TM} is shown here; the contact quality within Interactive Mode can be set when the 'Contact Quality' tab is clocked. Defaults include highest signal quality for all sensors, and noisy reference electrodes. Users can set each sensor individually.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.



☑ Enable Keystrokes

Enabled	Player	Name	Key(s)	Behavior	Target Application
☑	1	Move Up	d	☑ Send Once	<To application in focus>
☑	1	Move Down	c	☑ Send Once	<To application in focus>
☑	1	Push	a	☑ Send Once	<To application in focus>
☐	1	Pull	z	☑ Send Once	<To application in focus>
☐	1	Roll_l	h	☑ Send Once	<To application in focus>
☑	1	Roll_r	n	☑ Send Once	<To application in focus>

Trigger Conditions of <Push>

Enabled	Action	Trigger	Value
☑	Push	is equal to	1

Figure 3.7 EmoKey^{TM} is shown here; this programs sends keystrokes to specific programs, either selected beforehand, or whichever window is in focus. EmoKey^{TM} automatically connects to the Control Panel first and will receive input from the headset if the keystrokes are enabled; however, it can also connect to EmoComposer^{TM} and accept inputs.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

The software for integrating Emotiv SDK with other applications is written in C++, which allows improved user and programmer editing, as well as integration into existing programs for academic and research purposes. Furthermore, this allows greater speed than MATLAB, which runs on Java and therefore requires 20-30ms to call functions, limiting the possible speed for EEG usage. Whilst these can be integrated into existing software, they require significant C++ knowledge to implement. The specific decoding of individual EEG signals is not described by the general developer version of the software, though it is plausible that the decoding package for raw EEG data may have a more detailed description. For control of EmoKey^{TM} by EmoComposer^{TM}, instructions-defined as EmoScripts^{TM}-are written in EmoComposer Markup Language (EML), a variation of XML, and can be stored and edited as text files.

In terms of signal input, the EPOC^{TM} is designed to work with 3 Suites, which focus on facial expressions, subjective emotions, or conscious intent for movements. Users can practice on these individually before using them as part of existing software or can observe actions or linked key control schemes in emulator form to allow observation of results.

3.2 Association Between Hardware and Signal Quality

The Emotiv EPOC^{TM} Headset operates in a similar manner to the emulator, the primary difference being that it receives EEG input directly instead of through predefined scripts. This introduces an additional attribute of variable signal quality.

Unlike the fixed signal quality that can be set for the emulator, the physical Headset requires that the signal quality remain at the clearest possible in order to achieve direct translation of user inputs. These are described in Table 3.1 below.

Table 3.1 List of Emotiv EPOC^{TM} Headset Signal Quality Levels

Display Color	Signal Quality
Black	No signal
Red	Very poor signal
Orange	Poor signal
Yellow	Fair signal
Green	Good signal

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

The electrodes themselves are covered by white felt caps that must be moistened prior to wearing the Headset, these must be damp but not dripping, and require a period of adjustment once worn by the user. This is done by applying an isotonic saline solution originally used for cleaning contact lenses, and can be applied to the pads whilst inside their mountings, or by the first removing the pads and moistening both ends and the circumference.

Figures 3.8 and 3.9 show the electrodes beneath the pads as well as the connections behind the electrodes.

Figure 3.8 The EPOC^{TM} electrodes are shown here without the pads. The green coating on the surface is not corrosion, but an electrolytic coating painted onto the gold contact plate that can migrate due to saline application.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

Figure 3.9 An electrode removed from its mounting is shown here, and the accumulation of electrolytic coating is also visible. The electrode itself is removed by twisting the electrode clockwise, allowing to substitute individual pads, though there are currently no replacements listed in the Emotiv online store.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

Once the Headset has been affixed to the user, additional solution must be added in order to improve conduction between the pads, the hair and the scalp. A period of approximately 1 to 2 minutes as well as additional solution must be added to specific sensors to achieve the highest possible conductivity.

Once conduction has been achieved, it can be retained even at the highest levels for 2 to 3 hours without loss, provided the Headset remains in position; if improperly positioned however, user discomfort can reduce this time to 1 hour or less. From a preliminary standpoint, hair length may be a larger obstacle in maintaining sensor position instead of achieving optimal conductivity. According to Emotiv Systems, as of November 2009, conductive polymer pads are in development to replace the felt pads and current electrode design; however, a release date has not been announced yet, leaving verification for a later date.

3.3 Signal Suites for Evaluation

The EPOC^{TM} utilizes 3 Suites for detection of different signal inputs: Expressiv^{TM}, which reads facial expressions; Affectiv^{TM}, which reads the user's emotional state; and Cognitiv^{TM}, which reads conscious intent for movements.

In order to determine which of these Suites is most effective for hardware and software usage, users would need to train repetitively to perform the movements required of them in the case of the Expressiv^{TM} and Cognitiv^{TM} Suites, or to provide direct input for calibration and profile configuration in the case of the Affectiv^{TM} Suite.

In order to determine which Suite would be most effective in using the EPOC^{TM}, the Suites were first tested to determine the relative advantages and disadvantages. In addition, the iArm was tested using EmoComposer^{TM}, which reads scripts written in Emotiv Markup Language or EML, a variation of XML. These are known as EmoScripts^{TM}, and their use allows programmers to experiment with defined EmoStates^{TM} at specific times with specific changes in signal quality.

EmoKey^{TM}, which functions as an emulator by using traditional input devices. Whilst the C++ code which Emotiv^{TM} uses can be directly integrated into existing software, the use of specific key and word inputs that can be activated and deactivated selectively allows faster debugging and testing. Each keystroke input or Rule, has one or more Trigger Conditions which determine when the Rule applies. These use inputs from one or more Suites, when an EmoState^{TM} cannot be trained it either occurs or does not occur, or in the case of trainable or trained actions when it is equal to, not equal to, greater than or less than a number between 0 and 1 with a 2 d.p. accuracy. EmoKey^{TM}

saves collections of Rules and Trigger Conditions as Mappings that can be transferred between computers

3.3.1 Expressiv Suite – Facial Expression

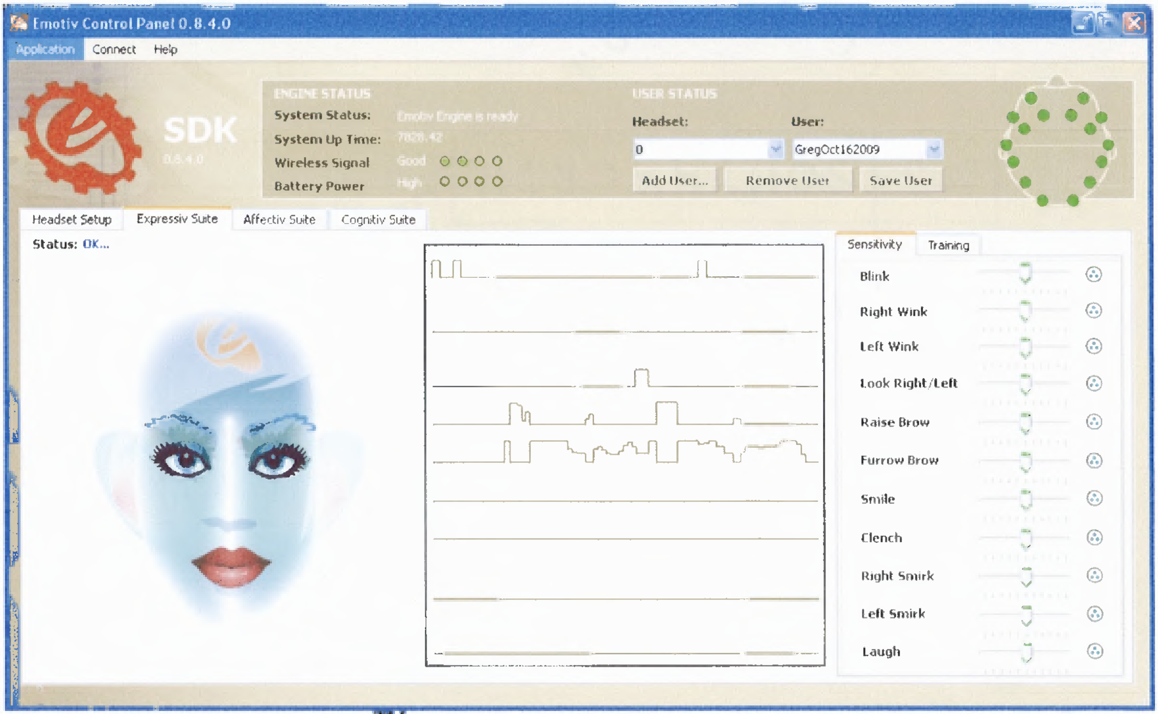
The Expressiv^{TM} Suite functions by reading the user's facial expressions. These are listed below in Table 3.2. Unlike the Affectiv^{TM} or Cognitiv^{TM} Suites, the Expressiv^{TM} Suite relies on signals sent to facial muscles; this reduces delay and gives a detection time in the range of 10 milliseconds. A list of expressions are given below in Table 3.2.

Table 3.2 List of Expressiv^{TM} Detection Event Signals

Expression	**Level Indications**			**Trainable**
	Low	**Medium**	**High**	
Blink	Non-Blink	N/A	Blink	No
Right Wink/Left Wink	Left Wink	No Wink	Right Wink	No
Look Right/Look Left	Look Left	Look Ahead	Look Right	No
Raise Brow	No Expression	Medium Expression	Maximum Expression	Yes
Furrow Brow	No Expression	Medium Expression	Maximum Expression	Yes
Smile	No Expression	Medium Expression	Maximum Expression	Yes
Clench	No Expression	Medium Expression	Maximum Expression	Yes
Right Smirk/Left Smirk	Left Smirk	No Smirk	Right Smirk	Yes
Laugh	No Expression	Medium Expression	Maximum Expression	Yes

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

The training program requires the user to train a given action before it can be used, and the result is defined as a Trained Signature. This requires that the user train for at least one trained and one neutral expression, requiring more time but allowing improved signal detection for each user involved. As shown in Table 3.2, not all expressions can be trained, specifically those related to eye and eyelid movements.



System Status: Emotiv Engine is ready
System Up Time: 7828.42
Wireless Signal: Good
Battery Power: High
Headset: 0
User: GregOct162009
Status: OK...

Figure 3.10 The Expressiv^{TM} Suite is shown here. Not all expressions can be trained, specifically Blink, Left/Right Wink and Look Right/Left. Look Right/Left and Right/Left Smirk have a single graph line each

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

3.3.2 Affectiv Suite – Subjective Emotions

The Affectiv^{TM} Suite functions by measuring changes in a user's subjective emotions. Unlike the Expressiv^{TM} and Cognitiv^{TM} Suites, these cannot be trained, but will instead be saved to the user's profile and used to improve detection rates for future use. Currently, 5 emotional states can be detected: engagement/boredom, frustration, meditation, instantaneous excitement and long-term excitement.

Engagement is characterized by focus and attention on specific tasks. In EEG terminology, this is defined as the presence of increased beta waves and attenuated alpha waves. Boredom is the opposite of this condition, and therefore the two states are represented by the same graph line.

Frustration is the reaction to opposition or disappointment, with focus on the sympathetic nervous system.

Meditation is a clearing of deliberate actions or intentions, with focus on the parasympathetic nervous system.

Instantaneous excitement is described as increased awareness, with focus on the sympathetic nervous system. Physiologically, it corresponds to pupil dilation, increased heart rate and sweat gland stimulation.

Long-term excitement is similar to instantaneous excitement, with the time length usually measured in minutes instead of seconds.

In the image below, the default settings display 30 seconds worth of data for engagement and instantaneous excitement on the top graph, and 5 minutes worth of data for long-term excitement on the bottom graph. These are rated on a relative scale of 0 to

1, as they are not direct units of measurement Unlike Expressiv™ or Cognitiv™, none of the listed states can be trained, but data can be used to update a user's profile.

System Status: Emotiv Engine is ready
System Up Time: 8649.66
Wireless Signal: Good
Battery Power: High
Headset:
User: GregOct162009

Status: OK...

Show	Color	Detection Name
☑	red	Engagement/Boredom
☑	blue	Frustration
☑	green	Meditation
☑	black	Instantaneous Excitement
☐	orange	Long Term Excitement

Display Length 30 Seconds

Show	Color	Detection Name
☐	red	Engagement/Boredom
☐	blue	Frustration
☐	green	Meditation
☐	black	Instantaneous Excitement
☑	orange	Long Term Excitement

Display Length 300 Seconds

Figure 3.11 The Affectiv™ Suite is shown here. The display durations for the graphs are shown, as well as which emotional state is being measured on a relative scale from 0 to 1.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

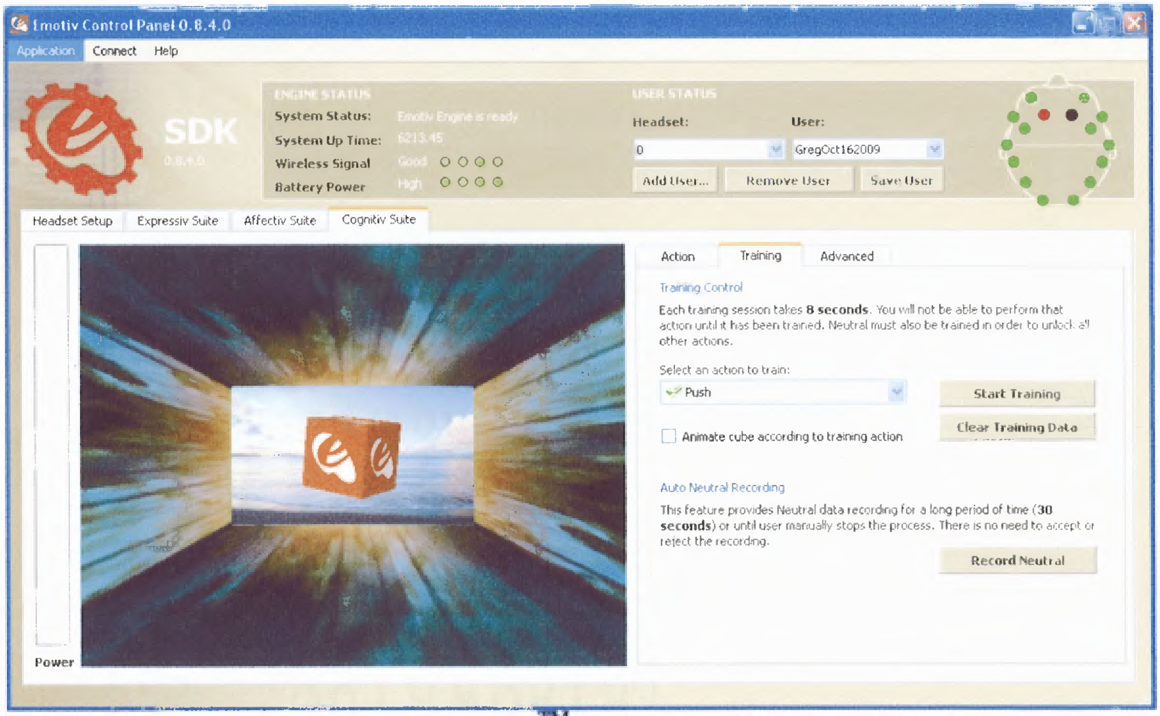
3.3.3 Cognitiv Suite – Movement Intentions

The Cognitiv^{TM} Suite focuses on a user's conscious intent to perform movements on objects, whether real or virtual. There are 13 in total, consisting of 6 directional movements with 2 in each axis, 6 rotations with 2 on each axis, and 2 additional actions: disappear-remove an object, and neutral-no actions. Table 3.3 lists the directions available in Cognitiv^{TM}.

Table 3.3 List of Emotiv EPOC^{TM} Cognitiv^{TM} Suite Movement Directions

Movement Name	Movement Type	Axis
Push	Directional	Z
Pull	Directional	Z
Left	Directional	X
Right	Directional	X
Up	Directional	Y
Down	Directional	Y
Clockwise	Rotational	Z
Counterclockwise	Rotational	Z
Left	Rotational	Y
Right	Rotational	Y
Forward	Rotational	X
Backward	Rotational	X
Disappear	Removal	None
Neutral	None	None

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.



System Status: Emotiv Engine is ready
System Up Time: 6213.45
Wireless Signal: Good
Battery Power: High
Headset: 0
User: GregOct162009

Training Control

Each training session takes **8 seconds**. You will not be able to perform that action until it has been trained. Neutral must also be trained in order to unlock all other actions.

Select an action to train: Push

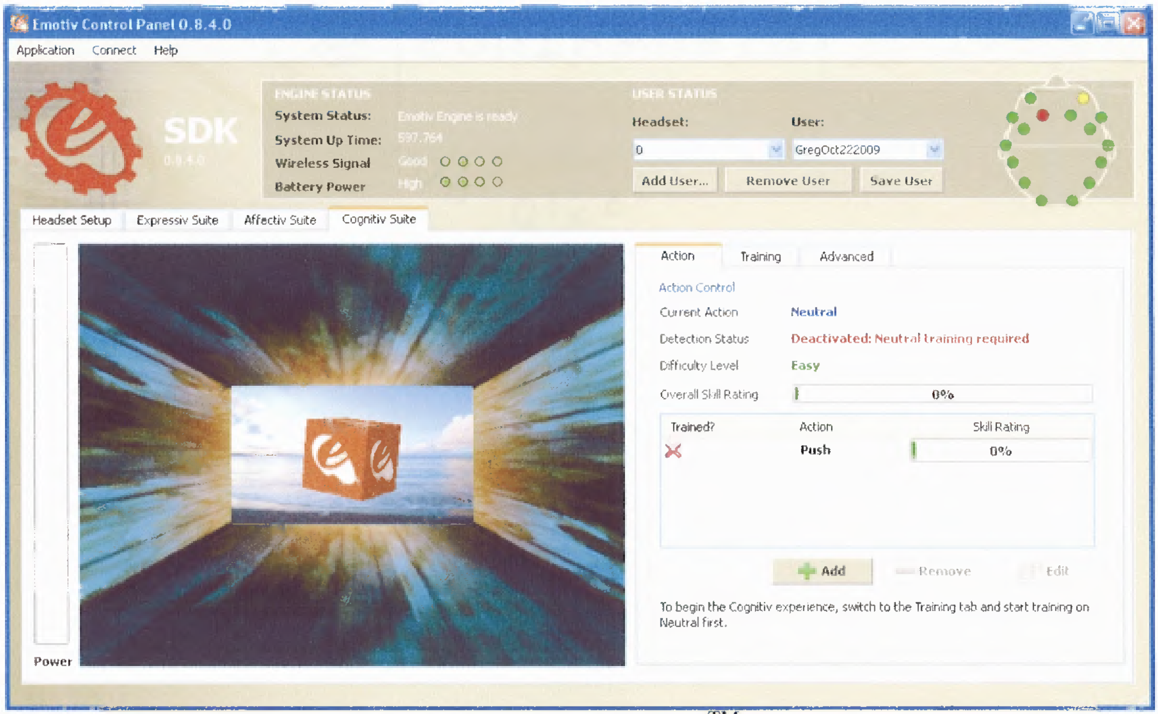
☐ Animate cube according to training action

Auto Neutral Recording

This feature provides Neutral data recording for a long period of time (**30 seconds**) or until user manually stops the process. There is no need to accept or reject the recording.

Figure 3.12 The initial tab for Cognitiv™ is shown here. A user's signature is updated with each action that is trained.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.



System Status: Emotiv Engine is ready
System Up Time: 597.764
Wireless Signal: Good
Battery Power: High
Headset: 0
User: GregOct222009

Current Action: Neutral
Detection Status: Deactivated: Neutral training required
Difficulty Level: Easy
Overall Skill Rating: 0%

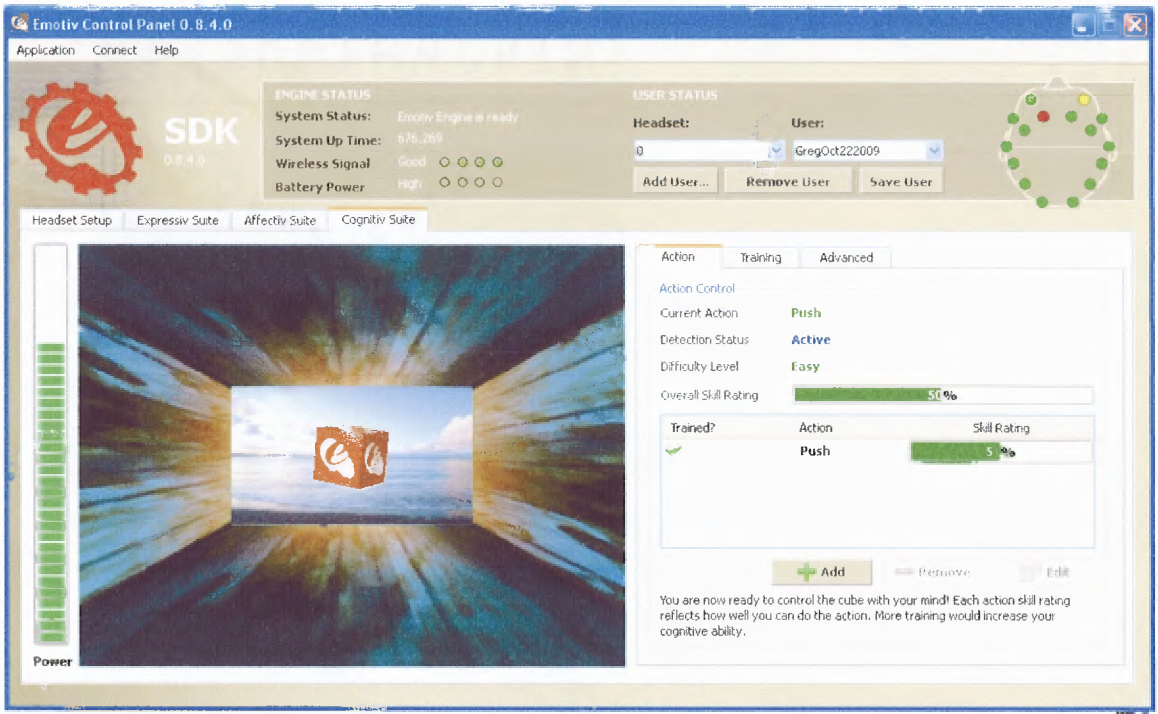
Trained?	Action	Skill Rating
✗	Push	0%

To begin the Cognitiv experience, switch to the Training tab and start training on Neutral first.

Figure 3.13 The Action tab is shown here in Cognitiv^{TM}. This lists all the actions trained by a given user. The current image is seen in the very beginning, as Neutral training is required first to provide a baseline, and Push is the default action to be trained afterwards.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

The Cognitiv^{TM} Suite allows up to 4 actions to be recognized at a given time, with the user defining each beforehand. The listed actions all require training from each user, and it is recommended to master specific actions individually before a user attempts to perform two or more actions concurrently. When an action is displayed, an accompanying action power value indicates the detection certainty that the user performed the listed action. The Skill Rating value shown is calculated from training, and indicates how consistently the user can mentally maintain a given action; this is updated after an action is trained at least twice. The Overall Skill Rating is the mean of the individual action skills. Unlike the Expressiv^{TM} Suite, all actions used in the Cognitiv^{TM} Suite-including Neutral-must be trained for the Suite to be active.



System Status: Emotiv Engine is ready
System Up Time: 676.269
Wireless Signal Good ○ ○ ○ ○
Battery Power High ○ ○ ○ ○

Headset: 0
User: GregOct222009

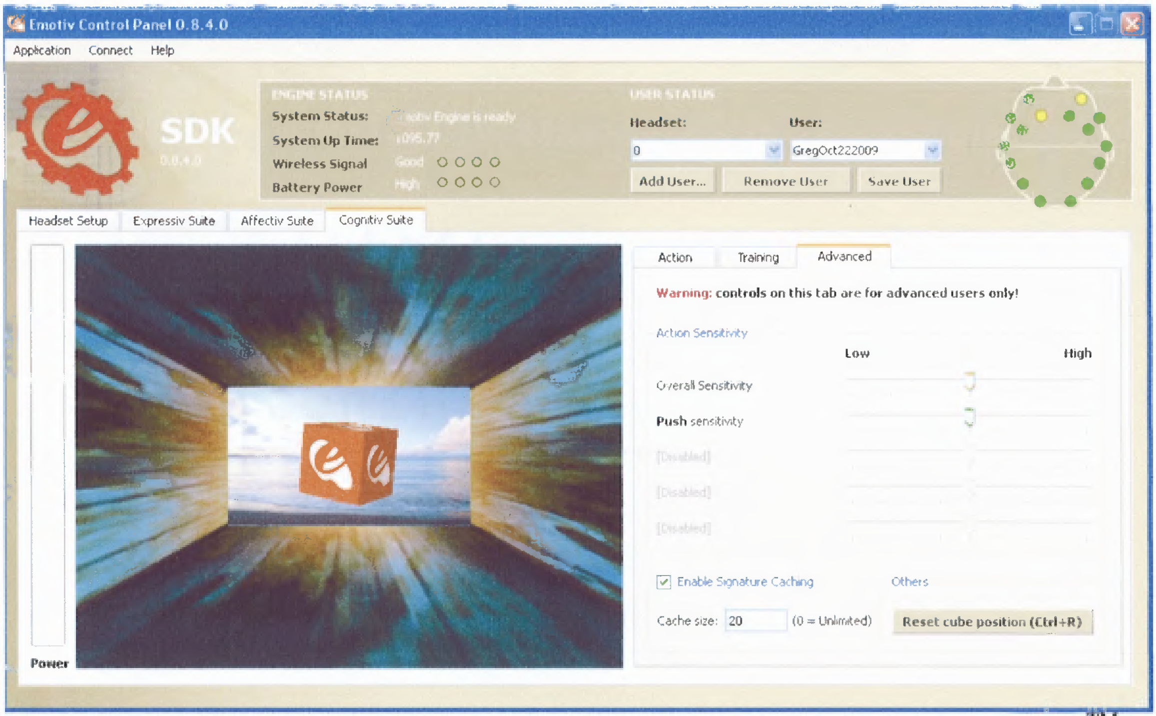
Action Control
Current Action Push
Detection Status Active
Difficulty Level Easy
Overall Skill Rating 50 %

Trained?	Action	Skill Rating
✓	Push	5 %

You are now ready to control the cube with your mind! Each action skill rating reflects how well you can do the action. More training would increase your cognitive ability.

Figure 3.14 This image shows the given skill rating for a trained Action in Cognitiv^{TM}, in this case Push. The Overall Skill Rating is an average of all the training sessions done by the user, and is updated after each session. Once an Action can be performed by the user, the Cube will move according to their intent, though as more actions are acknowledged, it becomes more difficult for Cognitiv^{TM} to discern each Action.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.



Headset: 0

User: GregOct222009

Warning: controls on this tab are for advanced users only!

Overall Sensitivity

Push sensitivity

[Disabled]

[Disabled]

[Disabled]

☑ Enable Signature Caching

Cache size: 20 (0 = Unlimited)

Figure 3.15 The adjustment sliders for sensitivity for the Actions in Cognitiv™ is displayed here, and only become available for each trained Action.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

In cube training, actions with training data have a green checkmark, whilst those without data have a red X. Once the Start Training Button is pushed, the user must maintain the listed mental state for approximately 8 seconds. During this time, the user may use hand gestures to aid in focus, but should limit head movement and facial expressions to avoid interference with the EEG signal. Training the Neutral mental state is also necessary to achieve an accurate baseline comparison, and at least 6 seconds are needed to update a user's profile.

The cube displayed on screen will not move until a specific action has been trained, but will move in future sessions by the user's input with a latency of up to 2 seconds. It is possible however for the cube to move automatically as a training aid whether the user performs the desired action or not. If a user becomes distracted and attempts to restart an action mentally, the results will be poorer than if the focus had lasted the full session. Once a training session is completed, the user has the option to accept or reject the most recent session, allowing them to decide whether the most recent session was optimally done. A session is automatically discarded if the wireless signal or the EEG signal quality was poor.

The primary difficulty encountered was the concentration needed to maintain a specific movement for the 8 seconds of each training session, and the ambiguity given for performing the specific command needed. In addition, as more actions were trained, it became more difficult to distinguish between their movements with Cognitiv$^{\text{TM}}$. Out of the given actions, the rotational movements proved much more difficult than the axial movements, with Push being the easiest to perform. However, even with daily sessions training this action, approximately 1 week was needed to reliably raise the accuracy to 50%.

3.4 Suite Evaluation for Use

In order to effectively evaluate the Emotiv EPOC$^{\text{TM}}$ headset, each of the 3 input Suites were tested without the use of neurological or neuromuscular disorders to determine which required the least training, with the greatest consistency, customizability and user responsiveness. The evaluator had no neurological or neuromuscular disorders in order to provide a baseline for comparison, and to evaluate the reliability and robustness of the EPOC$^{\text{TM}}$ prior to use by any subjects with such disorders.

The Expressiv$^{\text{TM}}$ Suite required no training in order to record user inputs, although it was necessary to specifically practice each of the usable facial expressions regardless of whether or not they were trainable. On the second day of practice with no prior training, a new user was able to perform each of the given facial expressions distinctly.

The Affectiv^{TM} Suite was able to recognize each of the multiple states listed without difficulty, but remains difficult to optimize for active control due to emotional states being primarily user responses to stimuli rather than directly controllable movements or intentions.

The Cognitiv^{TM} Suite was difficult to use because of the requirement for user training for each of the movements listed. The intention for a user to consciously move the training cube requires continuous mental effort for each of the 8 second training periods, diverting attention from any procedure which requires multitasking. In addition, the limit of only 4 actions possible at a given time in the current software version greatly constrains usage.

3.5 Suite Choice for iARM Experimentation

With the preliminary evaluation complete, the Expressiv^{TM} Suite is the primary choice for use in iARM Training due to the large number of possible movements, and 12 inputs compared to 5 for Affectiv^{TM}, and far greater controllability than Cognitiv^{TM}.

The next stage was to devise a testing procedure that evaluated user accuracy and responsiveness with the iARM peripheral.

CHAPTER 4

EMOTIV EPOC TRAINING AND EVALUATION WITH THE IARM USING DIRECT EEG INPUT

4.1 iARM Overview

The iARM is a robotic manipulator arm designed by the Netherlands-based company Exact Dynamics. Possessing 7 degrees of freedom, it is designed to be attached to a wheelchair due to its 9kg mass and size; the version used here is the right-handed version, although a left-handed version also exists. Figures 4.1-4.3 show the iARM in various positions.

Figure 4.1 The iARM is shown here in a folded position.
Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

BMIs have been used in previous studies as a control scheme for peripherals, including robots, that can remotely controlled by human or even primate brains (Kawato, 2008). Being able to achieve remote operation is a necessity for users who want to expand their range of movements, but signal delays or interference can occur, allowing the possibility of unintended or dangerous movements. Therefore, retaining the IARM within visual range of the user allows minimal delay between input and output.

Figure 4.2 The iARM stops in this position once the 'fold-out' command is given.
Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

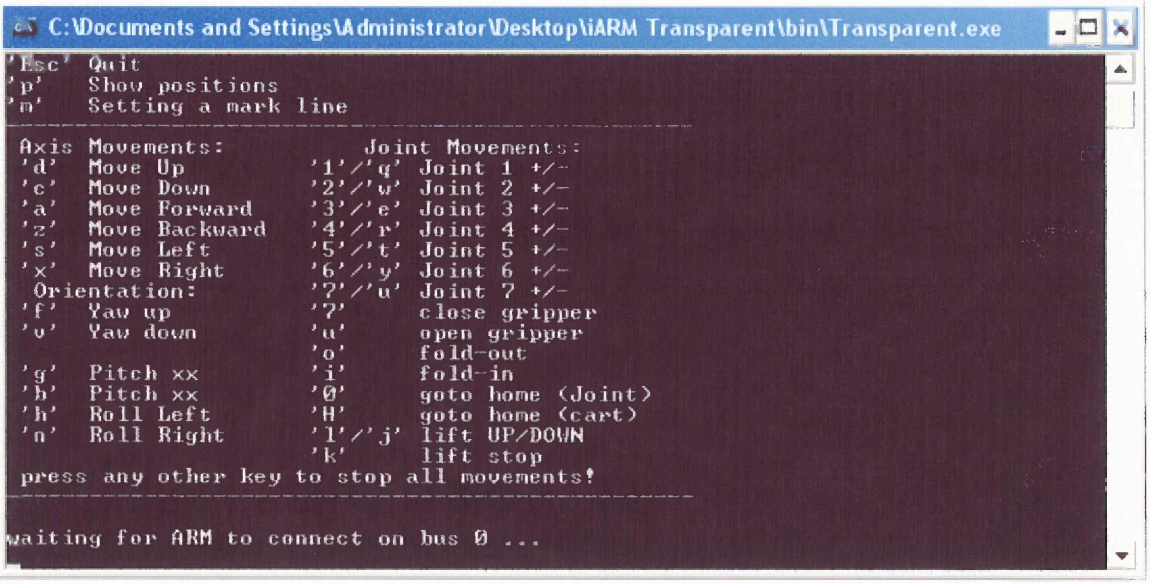
Figure 4.3 The iARM in a more stable position. This position can be maintained for longer periods of time than the previous one due to the reduced strain put on the joint motors, which is essential for repetitive testing. This position is also less likely to cause internal software errors, which require resetting of both hardware and software to resolve.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

Figure 4.4 The iARM LED display indicates its current status, as well as movement errors or software problems.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

The iARM software is written in MATLAB, allowing it to be integrating into existing software. However, it is also capable of being directly controlled by a provided program known as Transparent Mode. Because it can be controlled directly using single-key inputs, commands can be sent to it from a user's Expressiv inputs, which are in turn sent to EmoKey and then configured to output keystrokes to Transparent Mode.



```
'Esc'  Quit
'p'    Show positions
'm'    Setting a mark line
--------------------------------------------------------------------------------
 Axis Movements:            Joint Movements:
 'd'   Move Up              '1'/'q' Joint 1 +/-
 'c'   Move Down            '2'/'w' Joint 2 +/-
 'a'   Move Forward         '3'/'e' Joint 3 +/-
 'z'   Move Backward        '4'/'r' Joint 4 +/-
 's'   Move Left            '5'/'t' Joint 5 +/-
 'x'   Move Right           '6'/'y' Joint 6 +/-
  Orientation:              '7'/'u' Joint 7 +/-
 'f'   Yaw up               '7'     close gripper
 'v'   Yaw down             'u'     open gripper
                            'o'     fold-out
 'g'   Pitch xx             'i'     fold-in
 'b'   Pitch xx             '0'     goto home (Joint)
 'h'   Roll Left            'H'     goto home (cart)
 'n'   Roll Right           'l'/'j' lift UP/DOWN
                            'k'     lift stop
 press any other key to stop all movements!
--------------------------------------------------------------------------------

waiting for ARM to connect on bus 0 ...
```

Figure 4.5 Transparent Mode in accessed via an installed program on a PC connected to the iARM, and lists all the possible commands that cab be sent to the iARM.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

4.2 iARM Training Procedure

The primary measurement for user responsiveness for the combined Headset and iARM training will the ability to match and maintain a specific rhythm given by performing a given facial expression mapped to a corresponding iARM movement, and then changing the expression every 5 seconds.

In the experimental setup, the subject is seated out of the movement range of the iARM to avoid being hurt or inconvenienced by proximity movements, and the iARM is positioned to allow full movement range it each tested axis to avoid collisions with its surroundings. The planned initial procedure consisted of a total of 4 Axis Tests which challenged the ability of the user to differentiate between the different facial expressions within Expressiv^{TM} to move the iARM within a specific axis at a given periodicity. Each of the commands would be sent from EmoKey^{TM} to the Transparent Mode, and the resulting positional data would be recorded in a separate .dat file. This is then copied, converted into a .txt file and then graphed to show changes in position within each trial, the Axis Tests used are listed in Table 4.1.

Table 4.1 List of Axis Tests

	iARM Movements	**Facial Expression**	**Key**
Test 1 **Vertical Axis**	Up Down	Raise brow Furrow brow	d c
Test 2 **Horizontal Axis**	Push/Away Pull/Towards	Wink left Wink right	a z
Test 3 **Distal Axis**	Left Right	Left smirk Right smirk	s x
Test 4 **Gripper**	Open Gripper Close Gripper	Smile Clench	7 u
		N/A	Spacebar

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

Tests 1-4 would evaluate the user's ability to perform a single-axis movement; future trials would include combinations of the axes to move in two or three directions, and potentially a fixed path or sequence of directions to follow.

Each Axis Test was performed twice per day, with 3 consecutive days per week over a 2 week period for 2 subjects, and with each change in movement or 'beat' every 5 seconds for 21 seconds per trial. This gave a total of 5 changes, with the 1 second after the last to account for possible delays between the user expression and its acknowledgement by the Expressiv™ Suite.

Each of the given facial expressions served as a condition in EmoKey™ for 2 rules each with the same presets of triggering the action when the intensity was above 0.3. The time limit for each trial was performed using the website 'www.online-stopwatch.com', whilst rhythm was provided by the experimenter signaling the appropriate direction for the subject to move the iARM in every 5 seconds. As this was an audio cue, it allowed the subject to focus on the movement of the iARM, where a monotone sound would be more difficult to memorize and a visual cue would have been distracting. The position data was recorded by the iARM Transparent.exe software every 100 milliseconds, giving a sampling rate of 10Hz. This was well within range of the EPOC™ sampling rate, which is listed as 2048Hz.

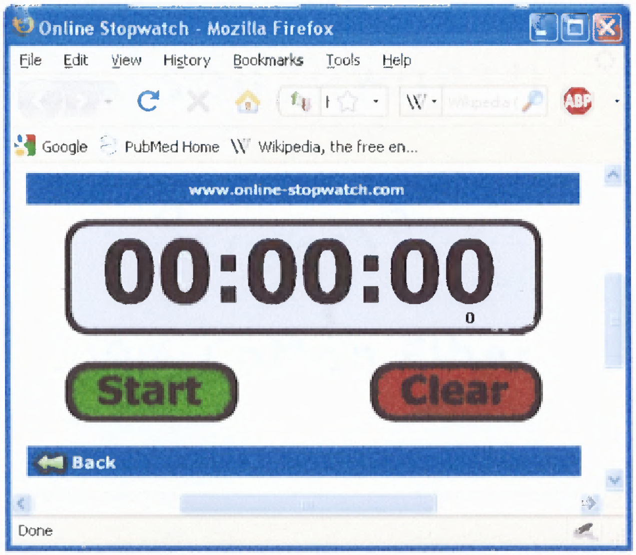


Figure 4.6 The website onlinestopwatch.com provided a means for the experimenter to retain control of EmoKey™ Mappings for each of the Axis Trials on a single PC, therefore decreasing possible errors resulting from multiple lab staff.
Source: Taken at NJIT BME Motor Control and Rehabilitation Lab
http://www.online-stopwatch.com/.

In order to avoid sending keystrokes after a Test was completed, the 'Enable Keystrokes' box was checked off after 21 seconds had elapsed, and the 'stop' command was sent in Transparent. This also provided a means of maintaining regularity, as the last change in position in the samples would be the end of the Test, and then approximately 210 samples earlier would be the starting point for each Test session.

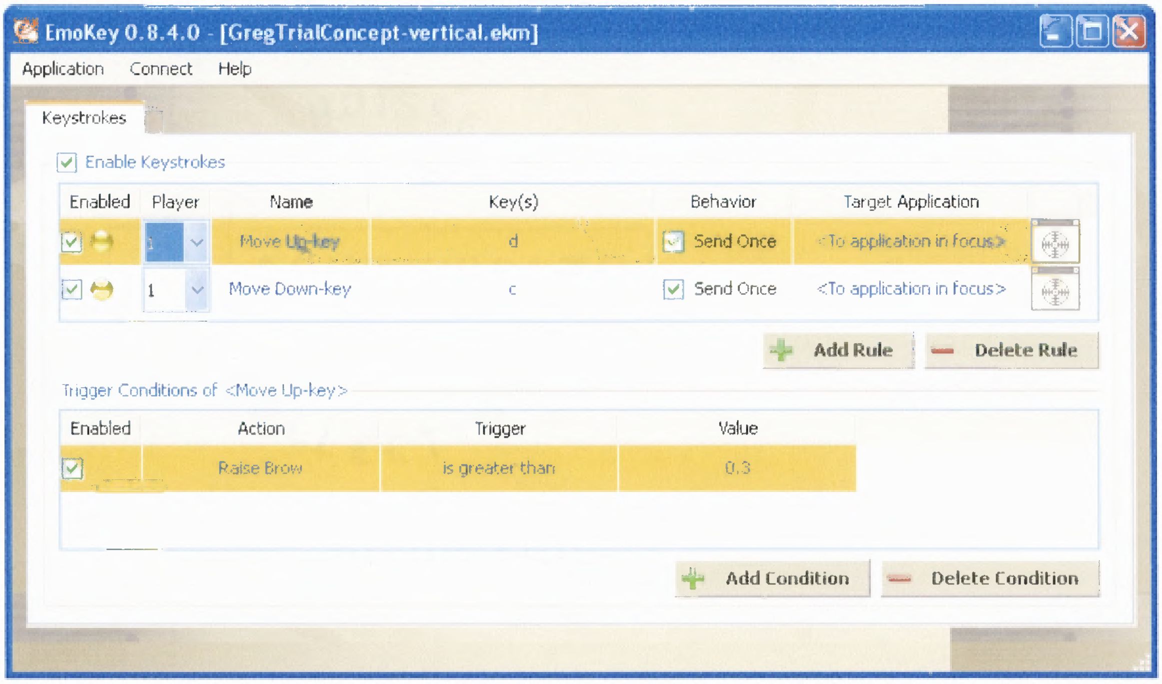
In the optimal case, each subject would have 5 position changes in each test, and a period of 50 samples between changes; fewer than 5 position changes or 50 samples and they would not be changing expressions when cued or frequently enough, greater than 5 position changes or 50 samples and they would be performing an incorrect facial expression.

Each user had no neurological or neuromuscular disorders in order to provide a viable baseline, and to evaluate the effectiveness of the training procedure for future patients who may have these conditions. User information is given below in Table 4.2, and a sample Mapping is given in Figure 4.7.

Table 4.2 Axis Tests Subject Information

Subject Initials	**Gender**	**Age**	**Hair Thickness-Top (cm)**	**Hair Thickness-Back (cm)**
QQ	Female	32	0.9	0.7
GF	Male	43	1.5	1.1

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.



☑ Enable Keystrokes

Enabled	Player	Name	Key(s)	Behavior	Target Application
☑	1	Move Up-key	d	☑ Send Once	<To application in focus>
☑	1	Move Down-key	c	☑ Send Once	<To application in focus>

Trigger Conditions of <Move Up-key>

Enabled	Action	Trigger	Value
☑	Raise Brow	is greater than	0.3

Figure 4.7 The Mapping for Axis Test 1 is shown here. Furrow Brow corresponds to 'move down', and has the same threshold value as Raise Brow. EmoKey^{TM} does not record a window's number once it is closed, and if reopened, will give it a different number to identify it. Therefore, the Transparent.exe window was selected just prior to each Axis Test to transfer user commands.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

4.3 Subject Training Results

The overall results for positions for each subject within each Axis Trial on a weekly basis is shown below in Figures 4.8-4.23. Each series indicates a trial session, with Series 1 and 2 representing day 1 of the week in question, Series 3 and 4 representing day 2, and Series 5 and 6 representing day 3. The exception to this is Figure 4.20, in which the two Series represent day 3 of week 1.

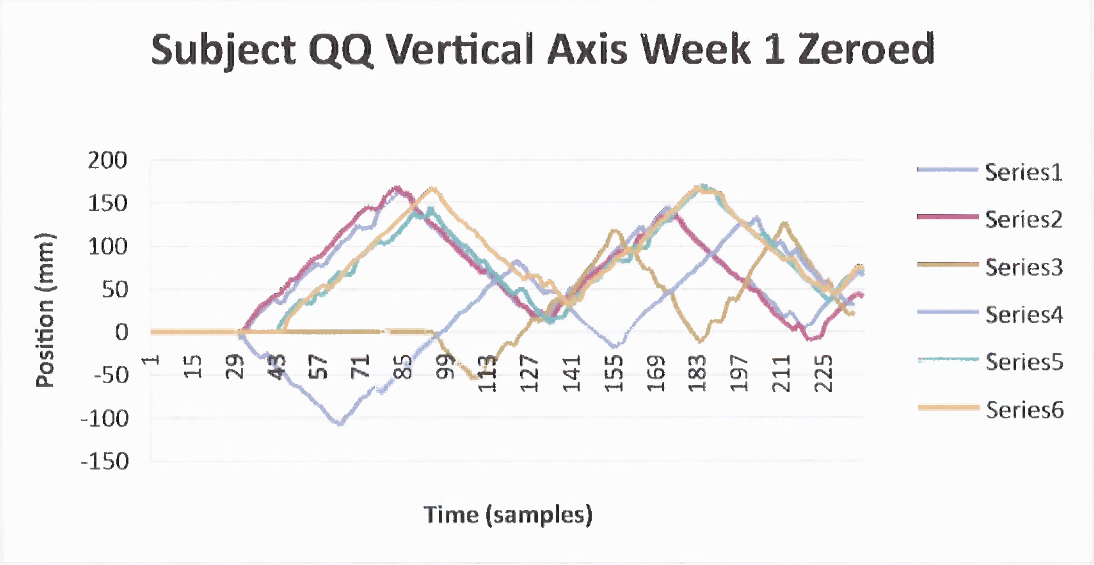


Figure 4.8 Subject QQ Vertical Axis Test – Week 1 Zeroed.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

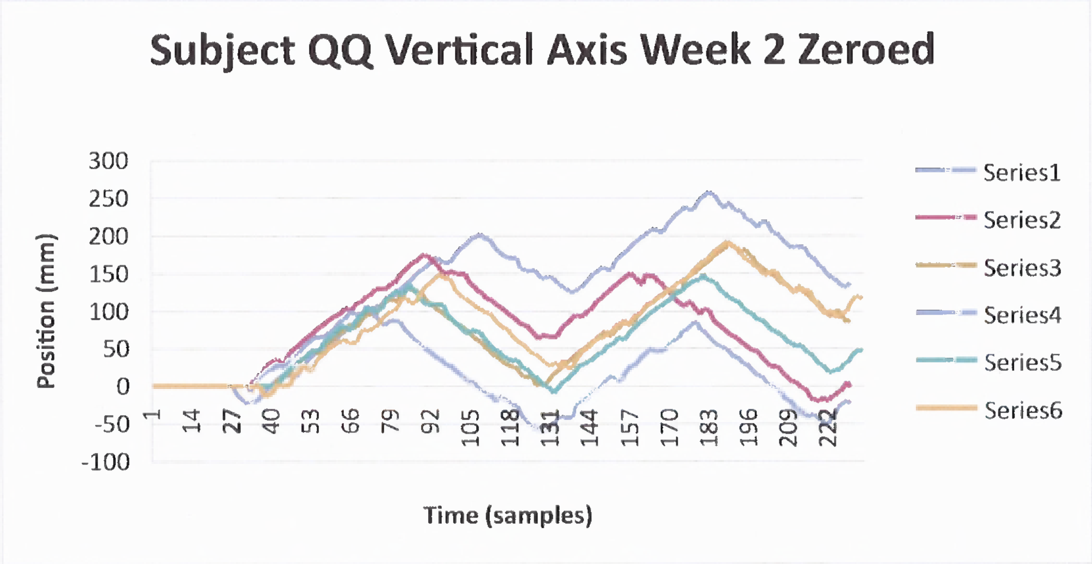


Figure 4.9 Subject QQ Vertical Axis Test – Week 2 Zeroed.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

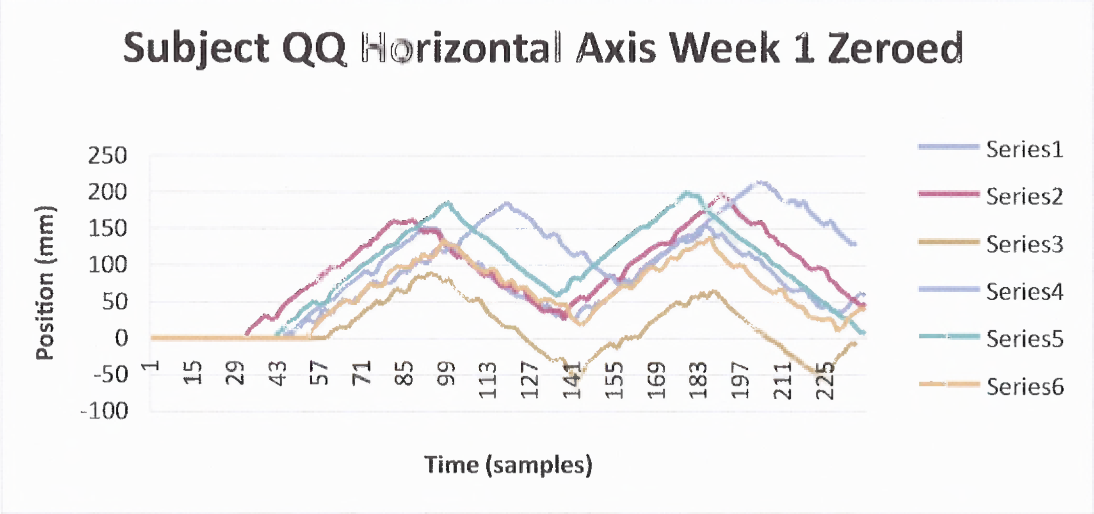


Figure 4.10 Subject QQ Horizontal Axis Test – Week 1 Zeroed.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

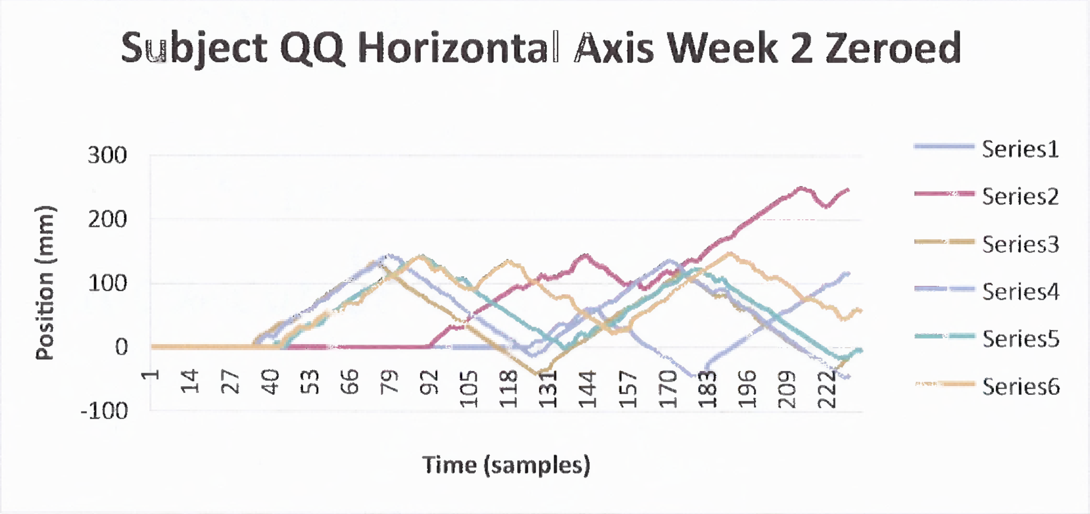


Figure 4.11 Subject QQ Horizontal Axis Test – Week 2 Zeroed.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

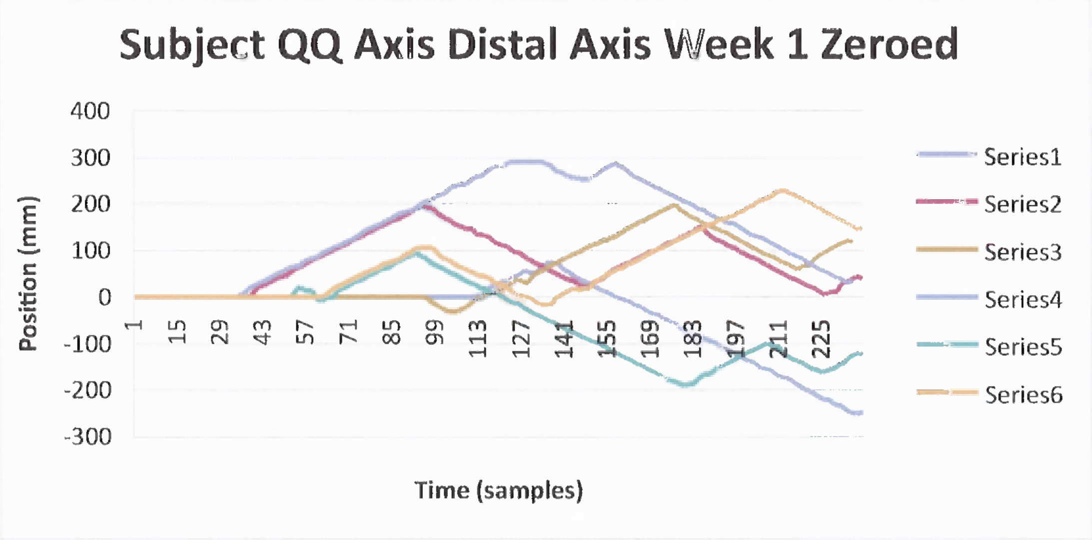


Figure 4.12 Subject QQ Distal Axis Test – Week 1 Zeroed.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

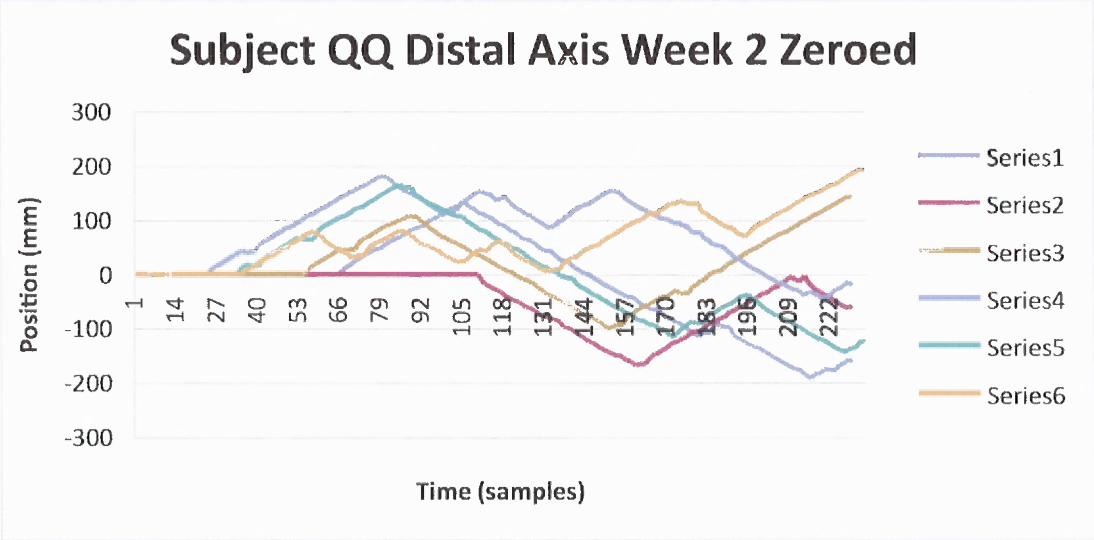


Figure 4.13 Subject QQ Distal Axis Test – Week 2 Zeroed.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

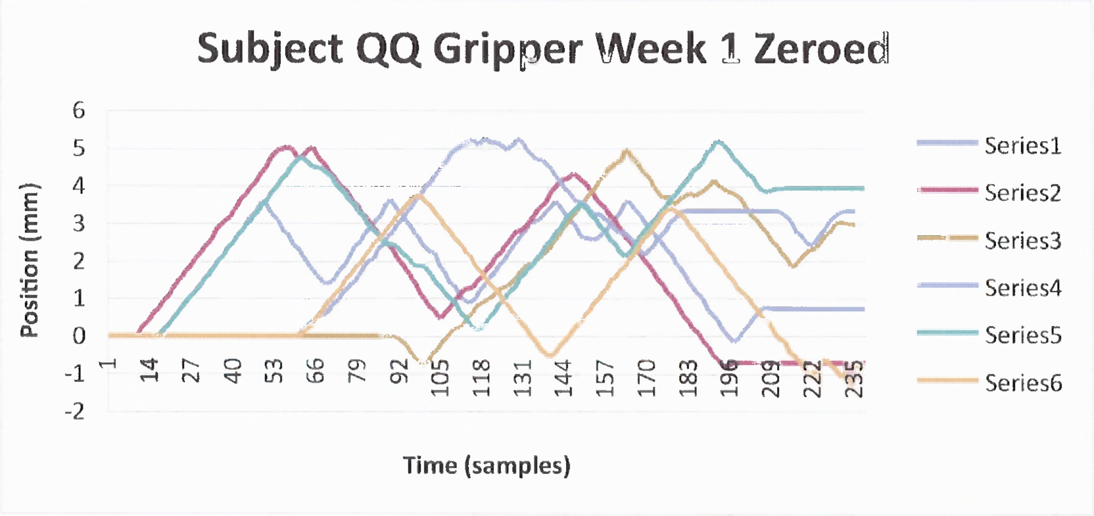


Figure 4.14 Subject QQ Gripper Test – Week 1 Zeroed.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

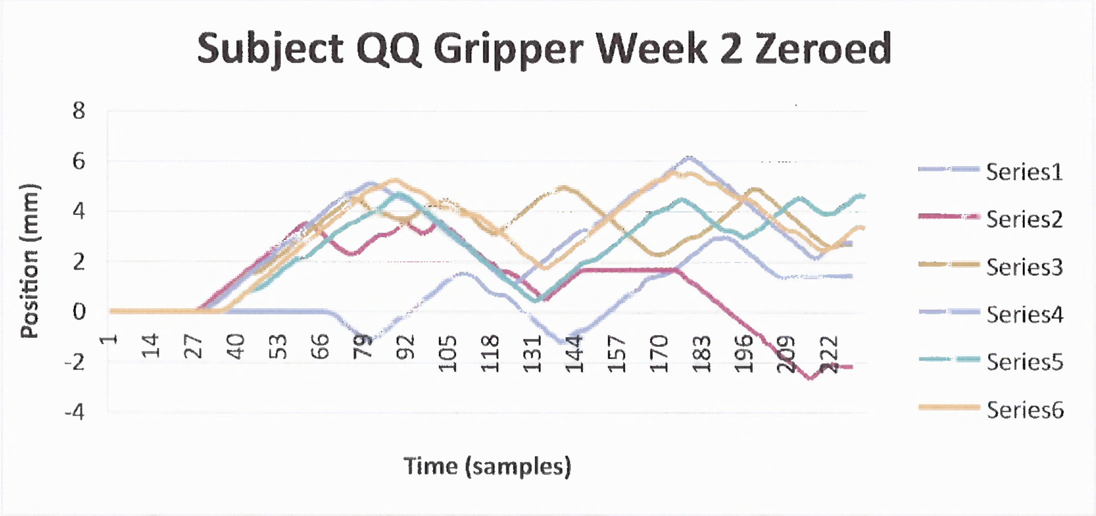


Figure 4.15 Subject QQ Gripper Test – Week 2 Zeroed.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

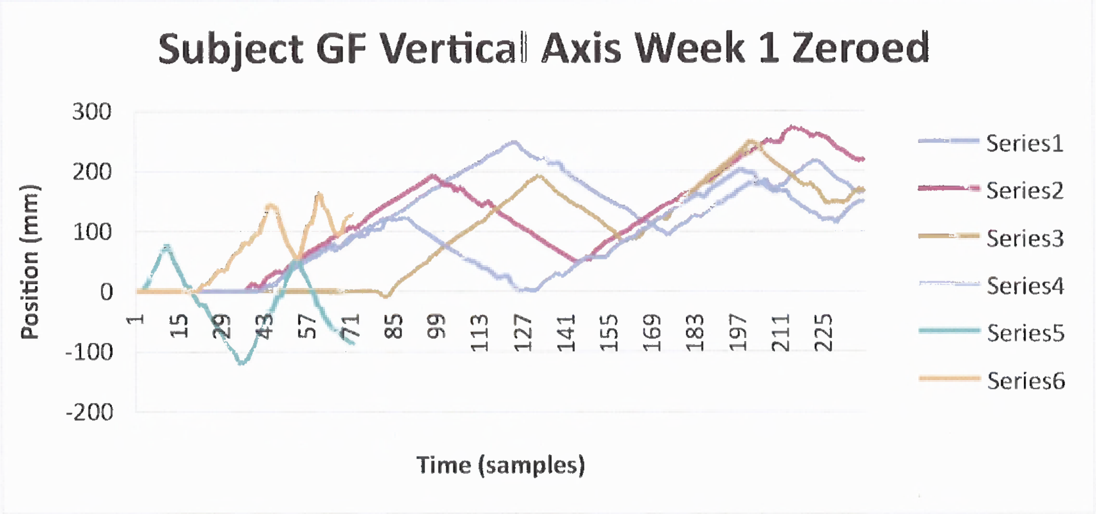


Figure 4.16 Subject GF Vertical Axis Test – Week 1 Zeroed.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

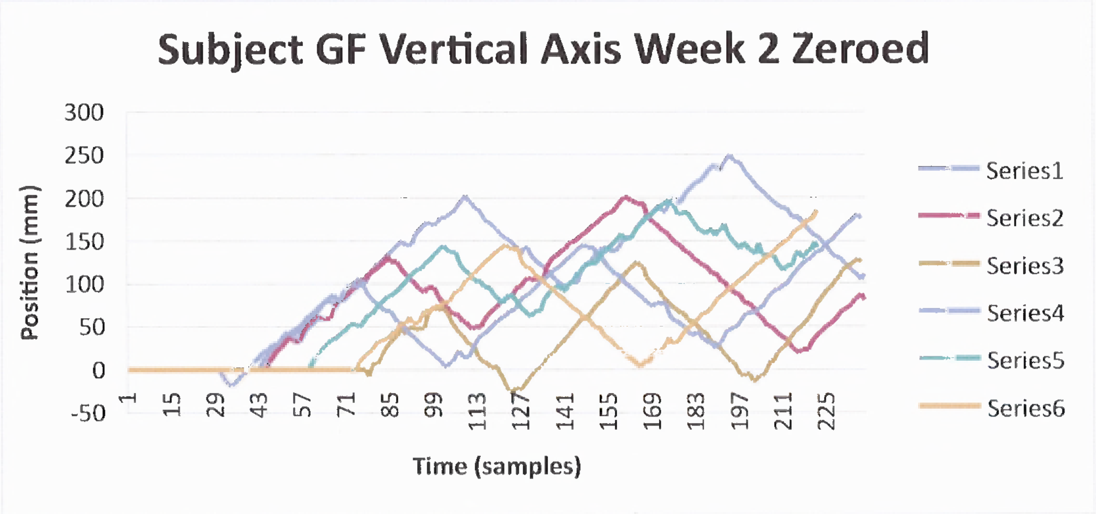


Figure 4.17 Subject GF Vertical Axis Test – Week 2 Zeroed.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

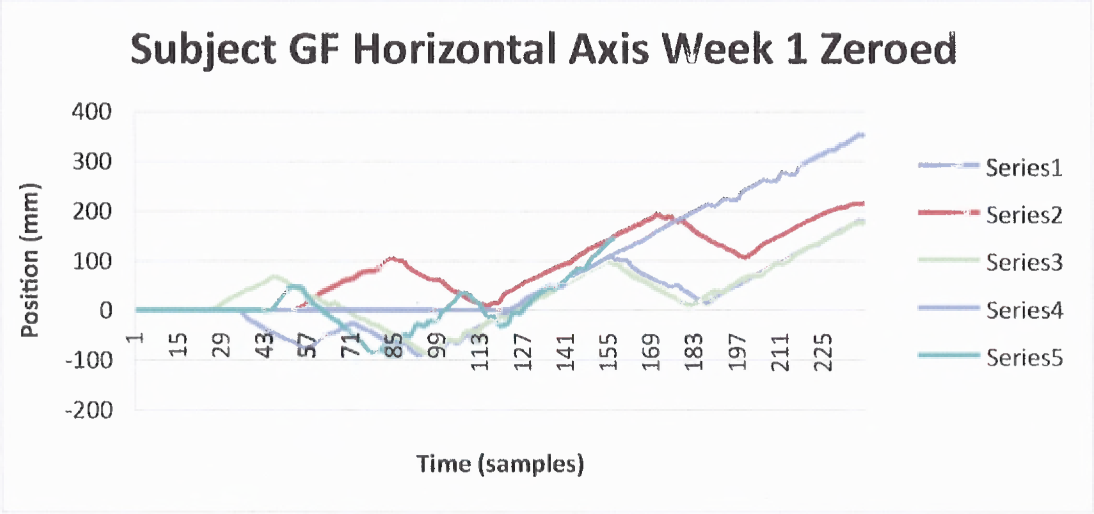


Figure 4.18 Subject GF Horizontal Axis Test – Week 1 Zeroed.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

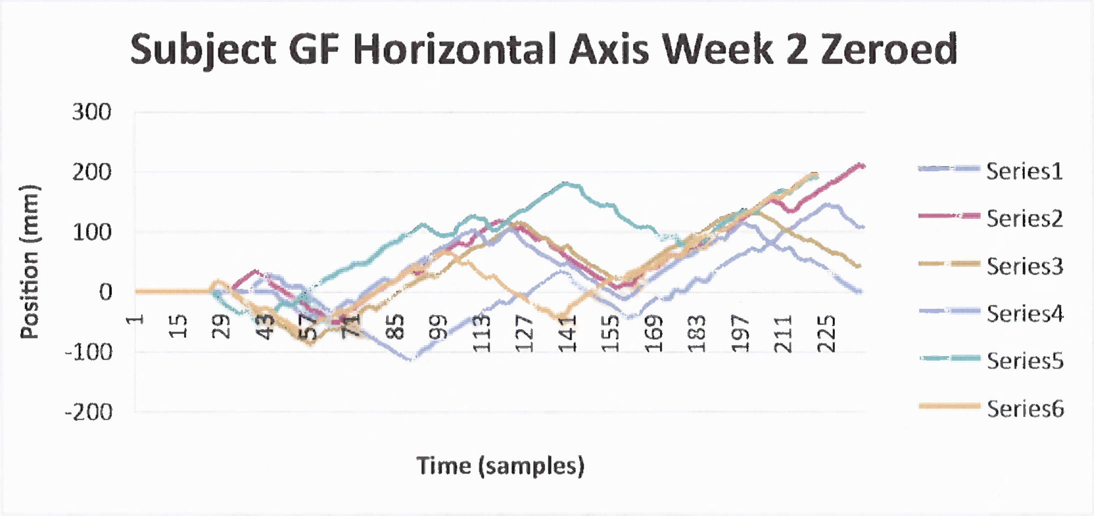


Figure 4.19 Subject GF Horizontal Axis Test – Week 2 Zeroed

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

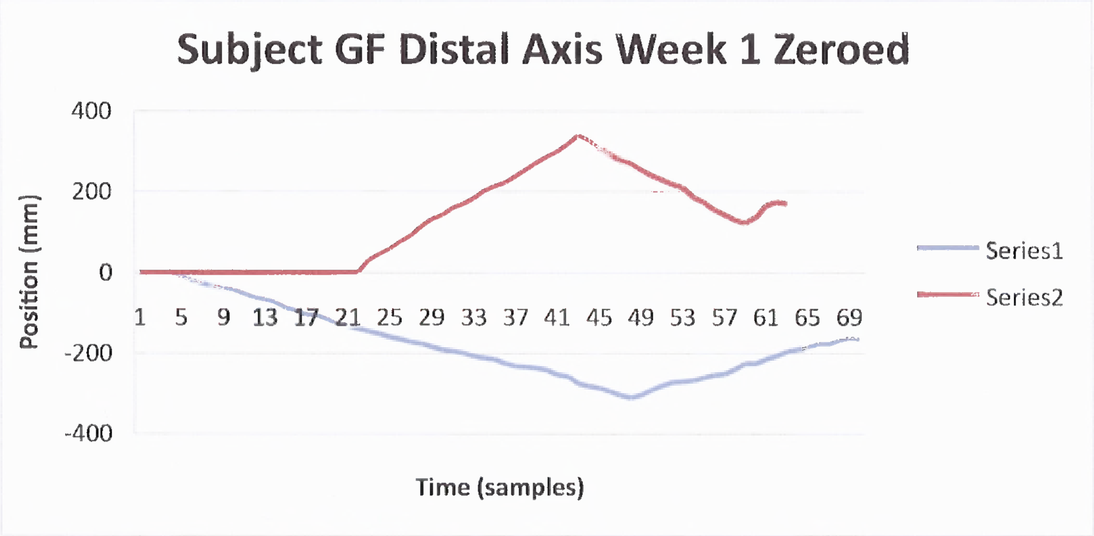


Figure 4.20 Subject GF Distal Axis Test – Week 1 Zeroed.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

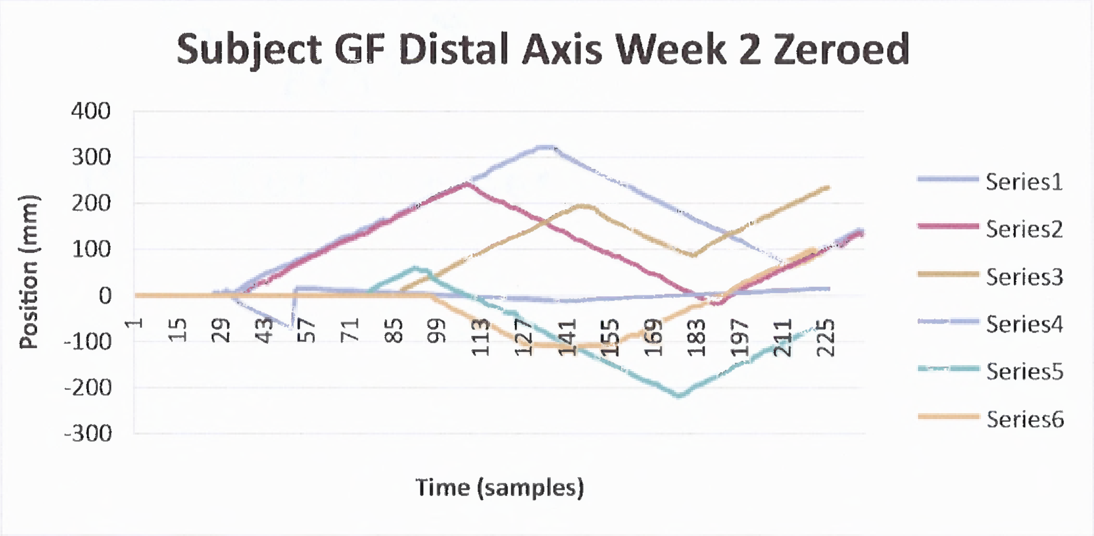


Figure 4.21 Subject GF Distal Axis Test – Week 2 Zeroed.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

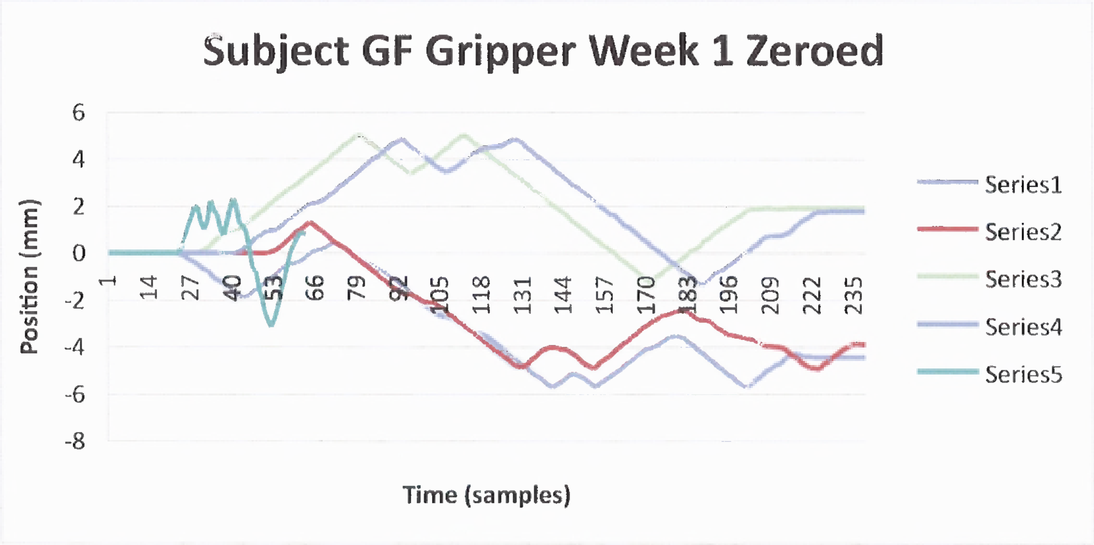


Figure 4.22 Subject GF Gripper Test – Week 1 Zeroed.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

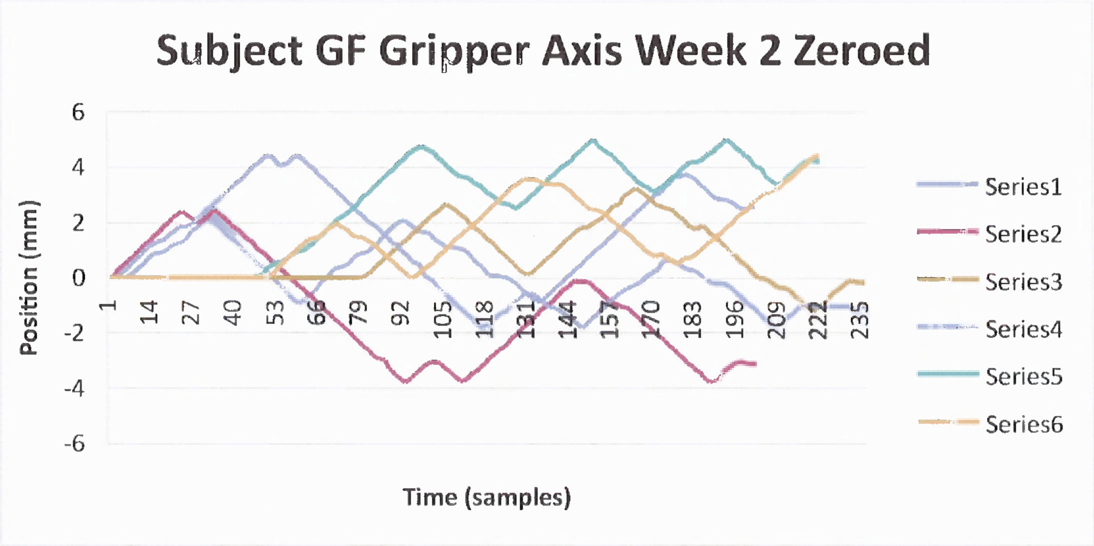


Figure 4.23 Subject GF Gripper Test – Week 2 Zeroed.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

The planned dual and triple Axis Test for each user were unable to be evaluated immediately due to the time for each user to acclimate to the iARM. This was primarily due to the iARM becoming immobile due to an unaccustomed position, requiring manual repositioning after each trial. Furthermore, despite the controllability within the Expressiv^{TM} Suite as the highest of the 3 Suites and general lack of training required for immediate usage, individual users had difficulties with different facial expressions, either in performing them or distinguishing multiple, simultaneous variations.

Therefore, the focus was on performing single axis movements in Axis Tests 1-4, as even if a user would be unable to perform multiple axes sequentially or rehearse a specific 3 dimensional movement, they would have the possibility of mastering one or two of the three axes with a set of facial movements. With this in mind, future Mappings could be calibrated to switch between different axes, but retain the same facial expressions as the input.

4.4 Analysis of Data

Within the training sessions for each of the subjects, there are both consistencies in movement as well as improvements. In the ideal case, the shape of the positional graphs would be a triangle wave due to the fixed velocity for the iARM in each axis.

After the initial day of testing, improvements in coordination and familiarity with the control system and their corresponding facial movements reduced the overall time of each of the four sessions from 1h 30 minutes to approximately 45 minutes by the end of day 3, and 30 minutes during week 2.

Both subjects improved or maintained their improvements from the first week to the second. For both subjects, the Vertical and Horizontal Axes showed the most consistent performances for all testing days, as these movements were most directly tied to facial movements. The Gripper proved to be more difficult partially because of the difficulty in performing the 'Clench' expression required by the software, as well as the delay in response time between the expression and the given movement. The Distal axis proved the most difficult for both subjects, specifically subject 2 who was unable to perform movements in both directions during the first 2 days of week 1. However, he was consistently able to perform Distal movements during each session of week 5.

Hair length was not found to be a hindrance to conduction and signal quality for either subject when the pads were sufficiently moist, thick hair was partner around each sensor and saline solution was added to the surroundings. For subject QQ however, her thicker hair did make sensor repositioning more difficult due to the obstruction of scalp contours.

The means of the periods in each Test are given below in Figures 4.24-4.31, and the standard deviations of those means are given in Figures 4.32-4.39. The period means for each x-axis value is the mean for a specific day.

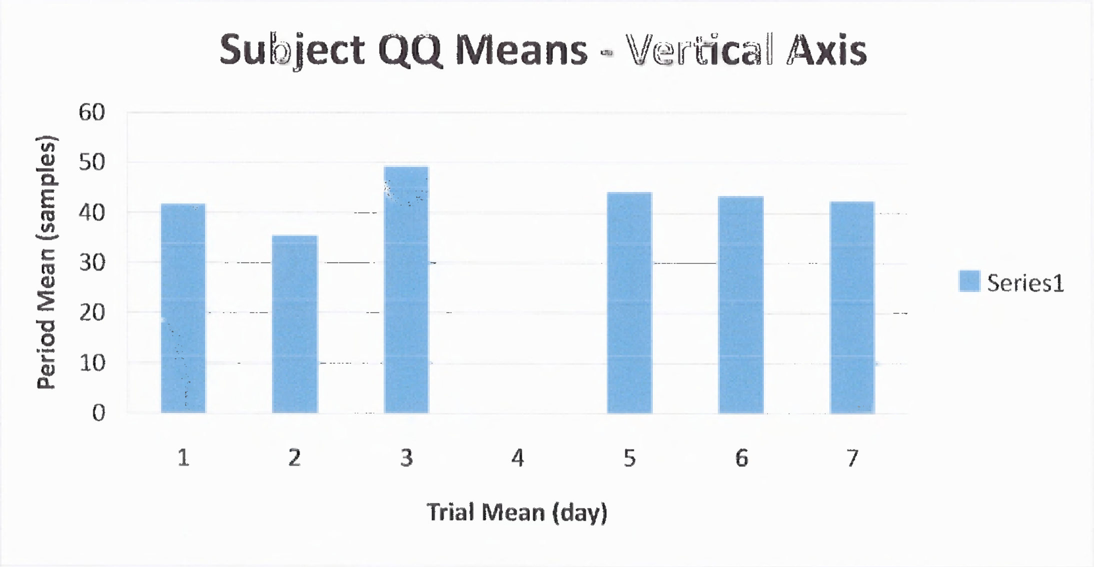


Figure 4.24 Subject QQ Period Means – Vertical Axis Test.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

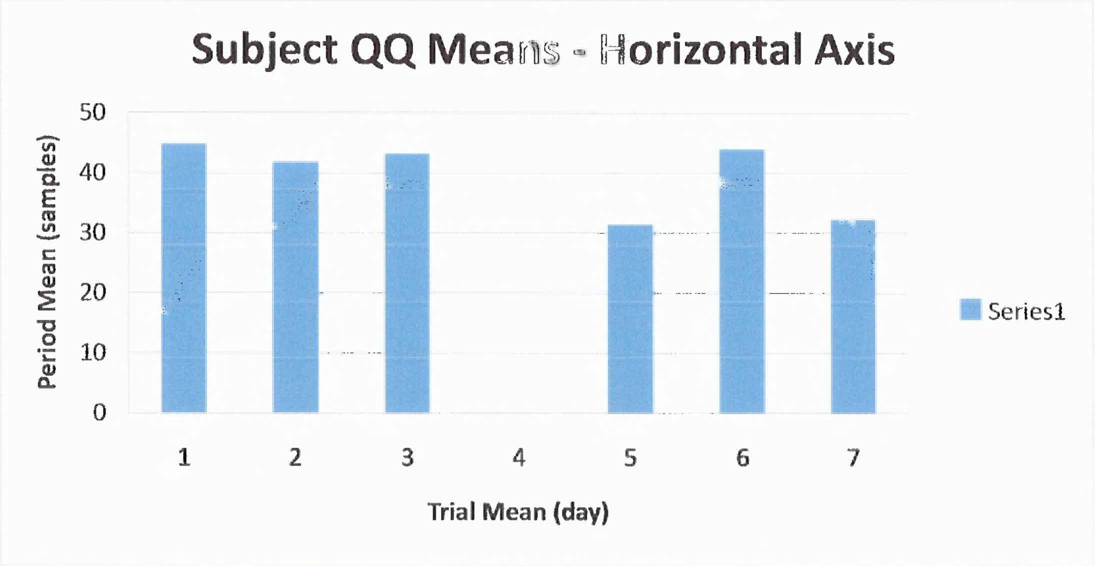


Figure 4.25 Subject QQ Period Means – Horizontal Axis Test.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

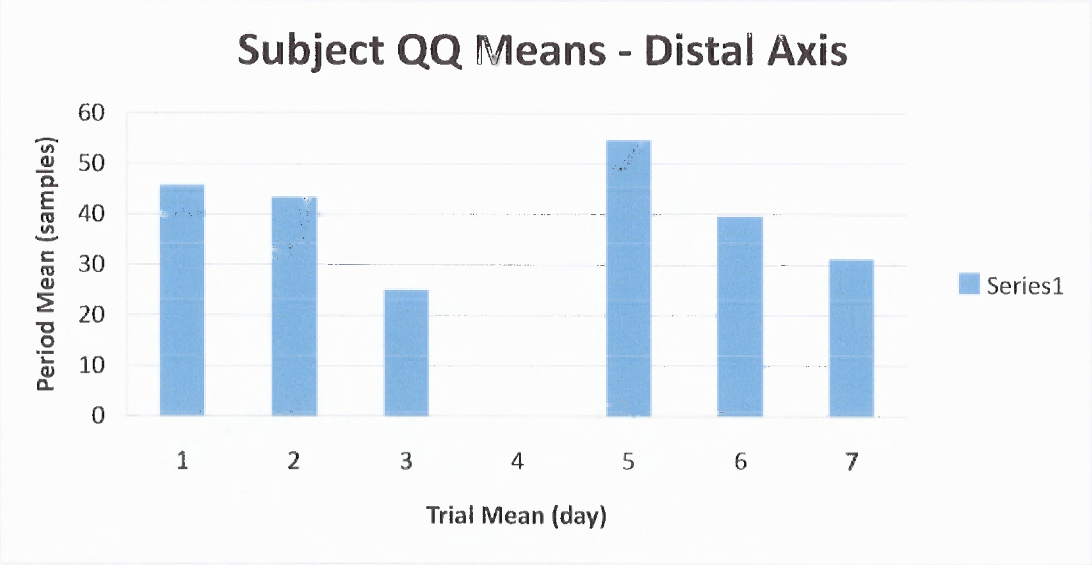


Figure 4.26 Subject QQ Period Means – Distal Axis Test.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

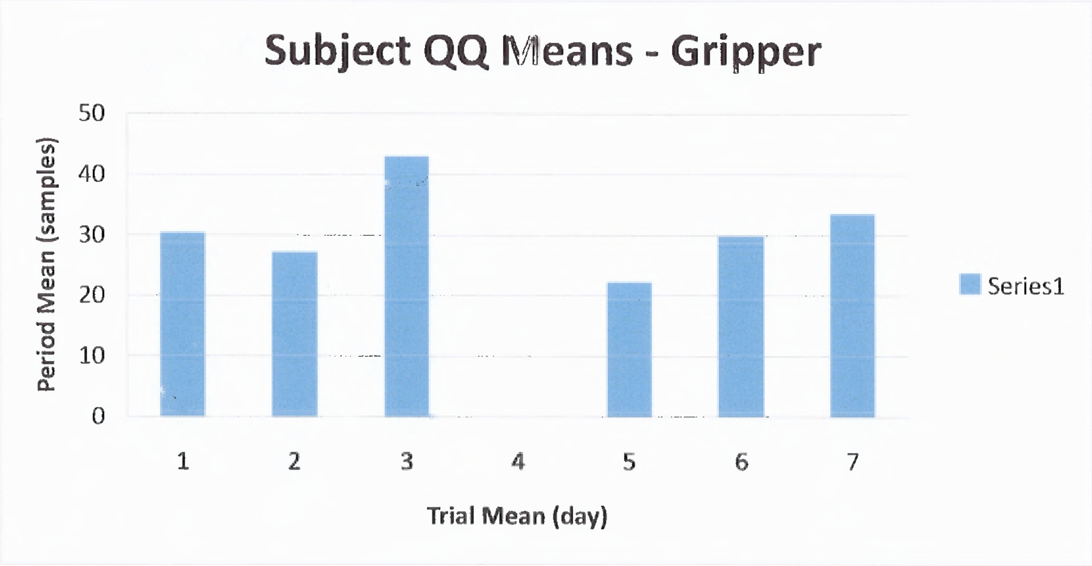


Figure 4.27 Subject QQ Period Means – Gripper Test.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

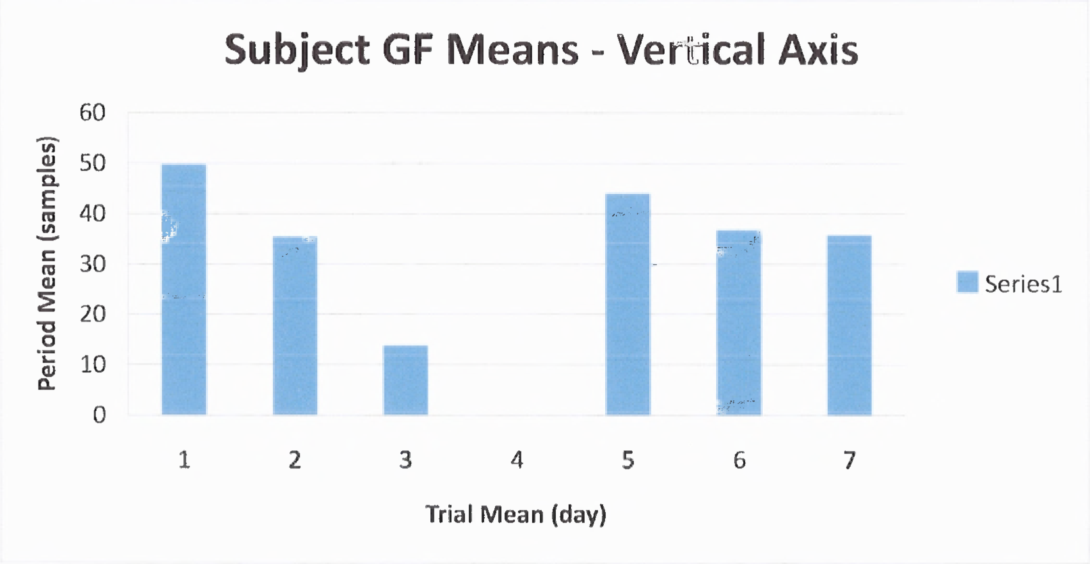


Figure 4.28 Subject GF Period Means – Vertical Axis Test.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

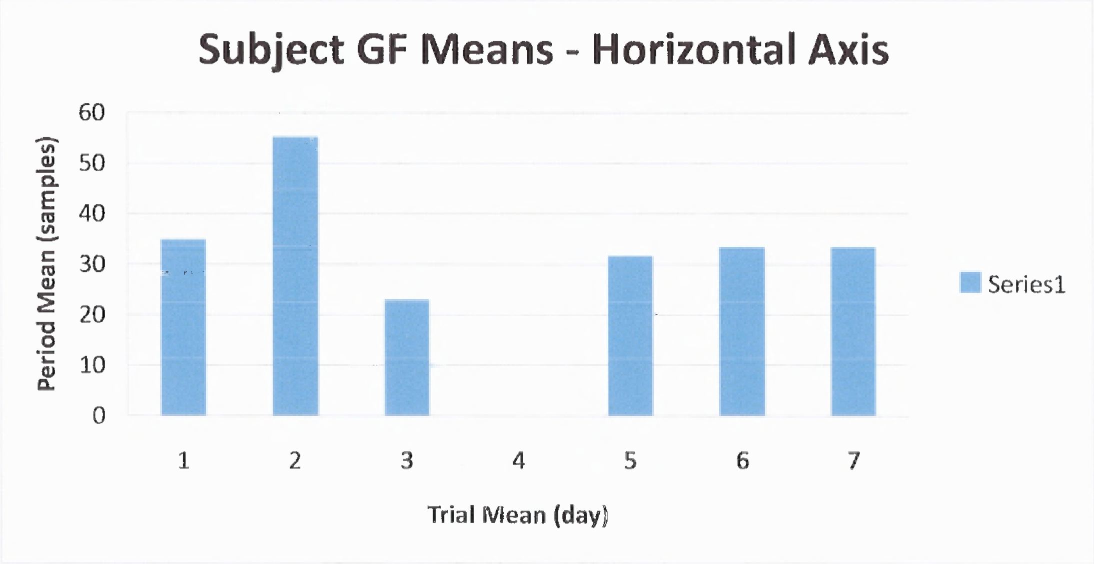


Figure 4.29 Subject GF Period Means – Horizontal Axis Test.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

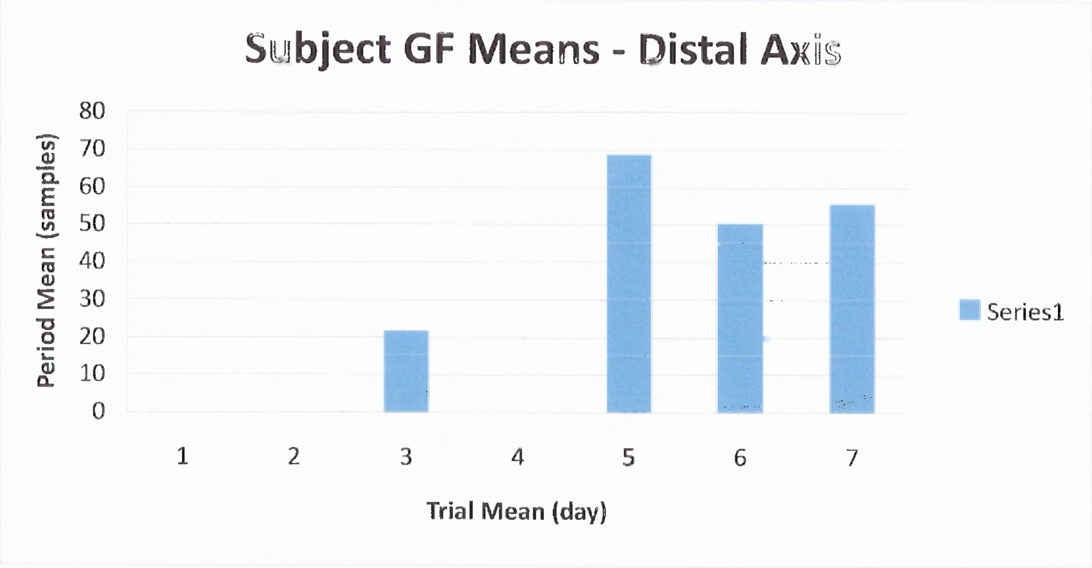


Figure 4.30 Subject GF Period Means – Distal Axis Test.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

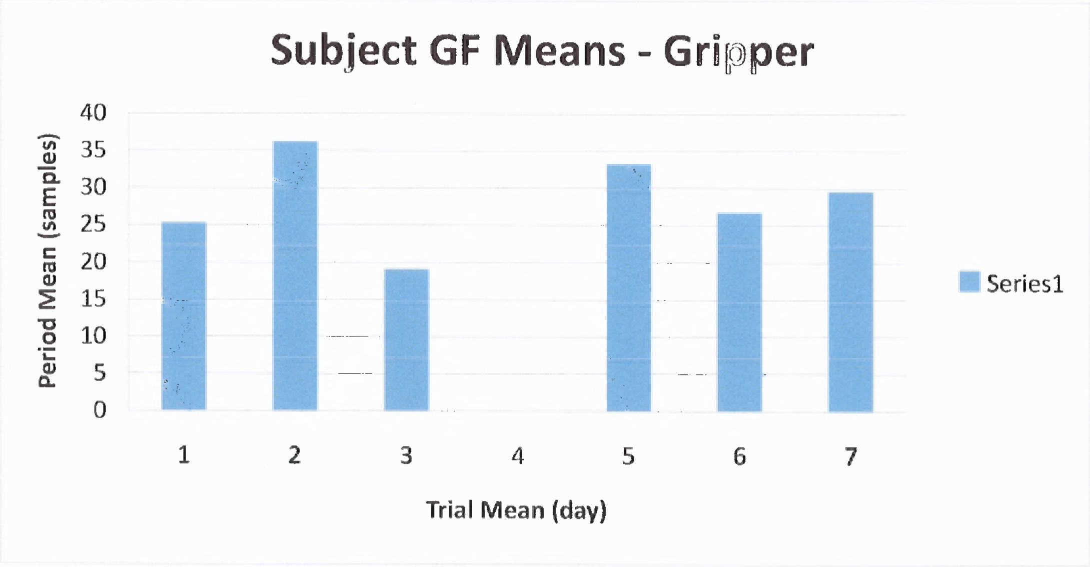


Figure 4.31 Subject GF Period Means – Gripper Axis Test.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

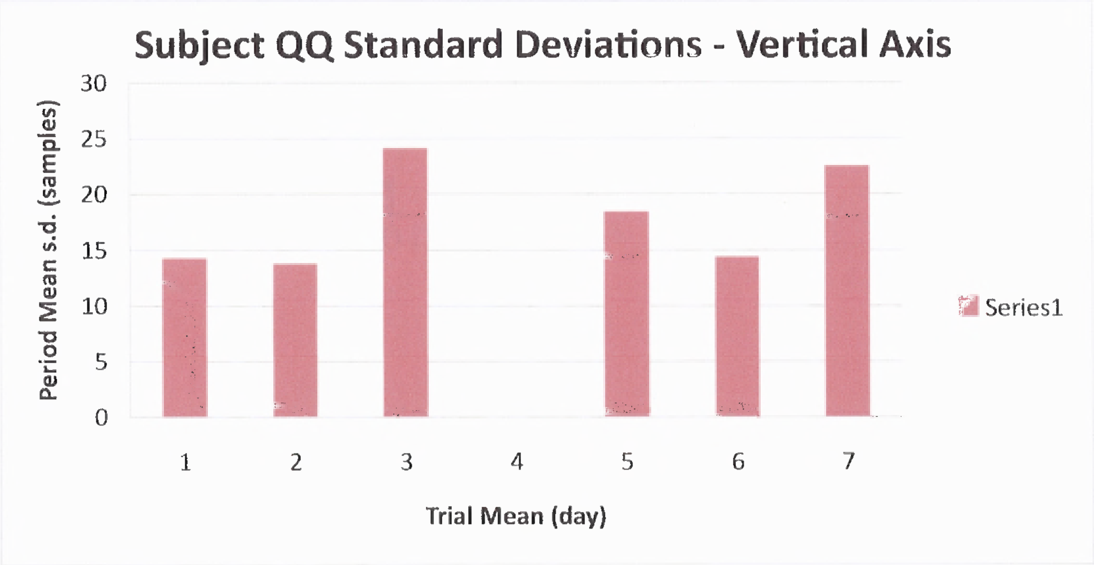


Figure 4.32 Subject QQ Period Length Standard Deviations – Vertical Axis Test.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

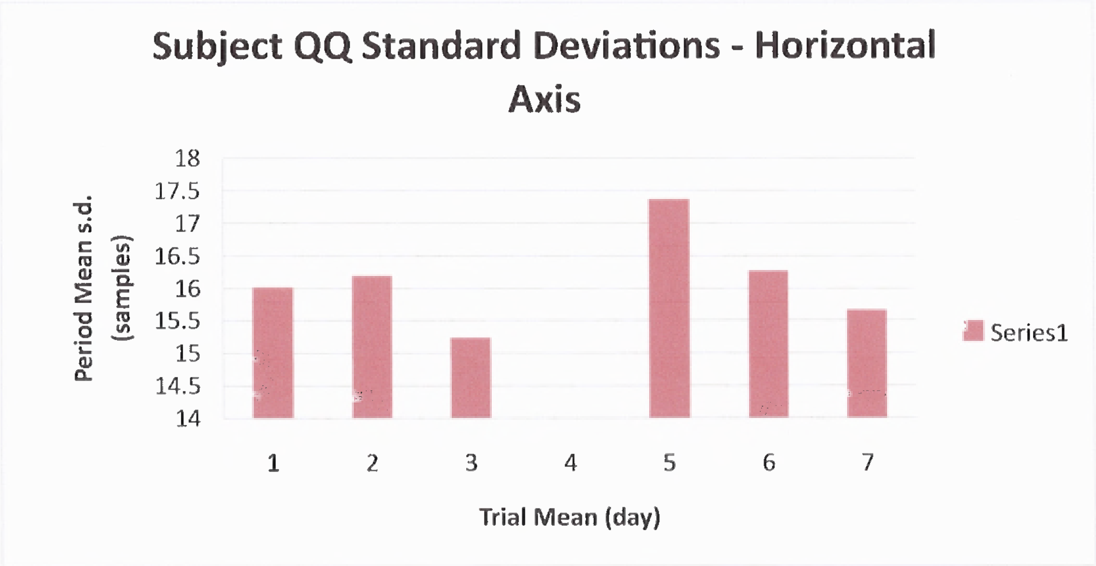


Figure 4.33 Subject QQ Period Length Standard Deviations – Horizontal Axis Test.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

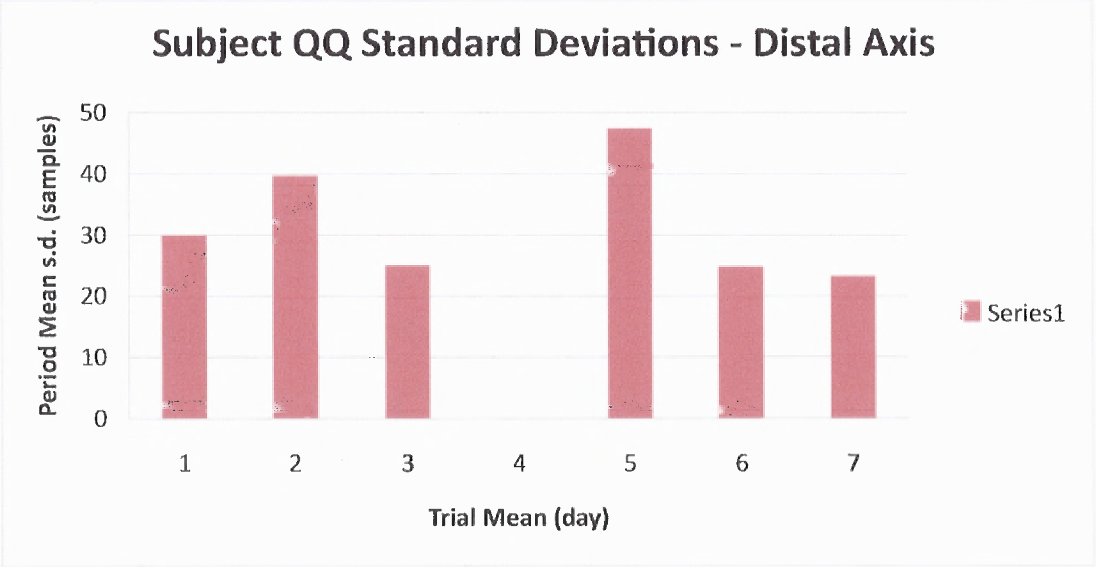


Figure 4.34 Subject QQ Period Length Standard Deviations – Distal Axis Test.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

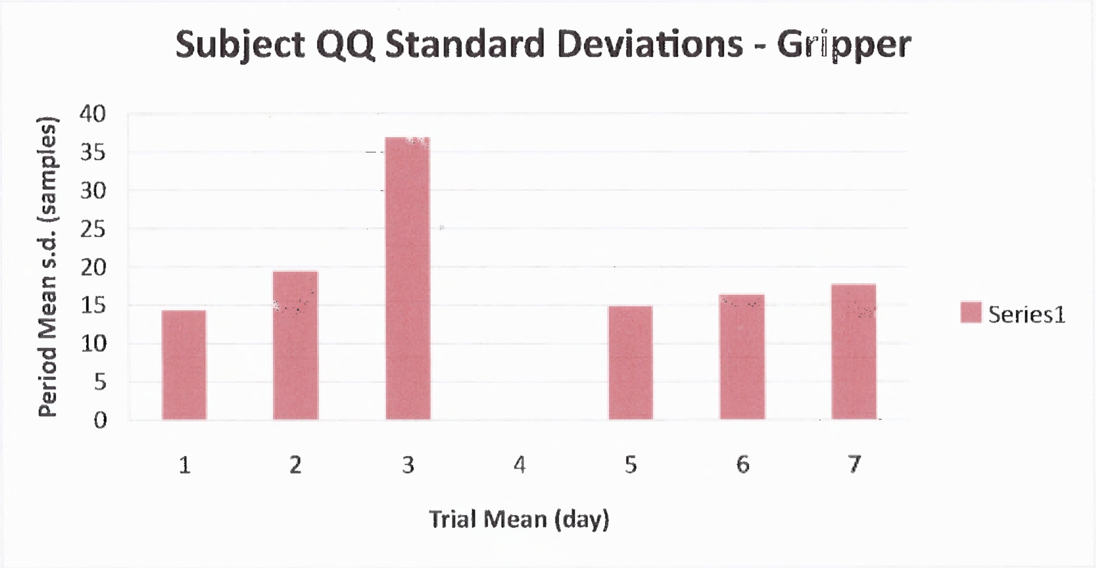


Figure 4.35 Subject QQ Period Length Standard Deviations – Gripper Test.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

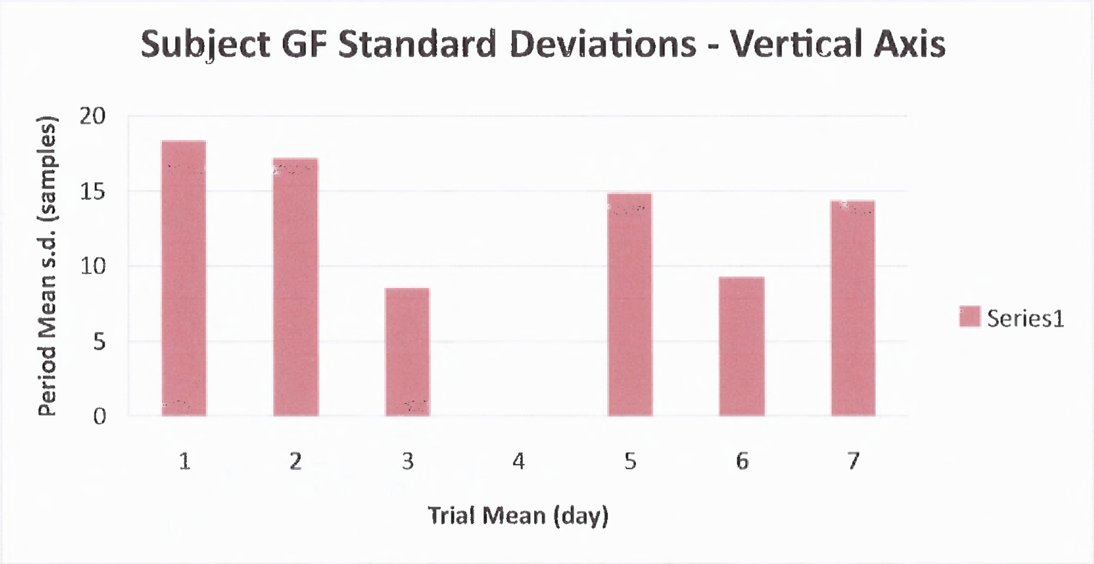


Figure 4.36 Subject GF Period Length Standard Deviations – Vertical Axis Test.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

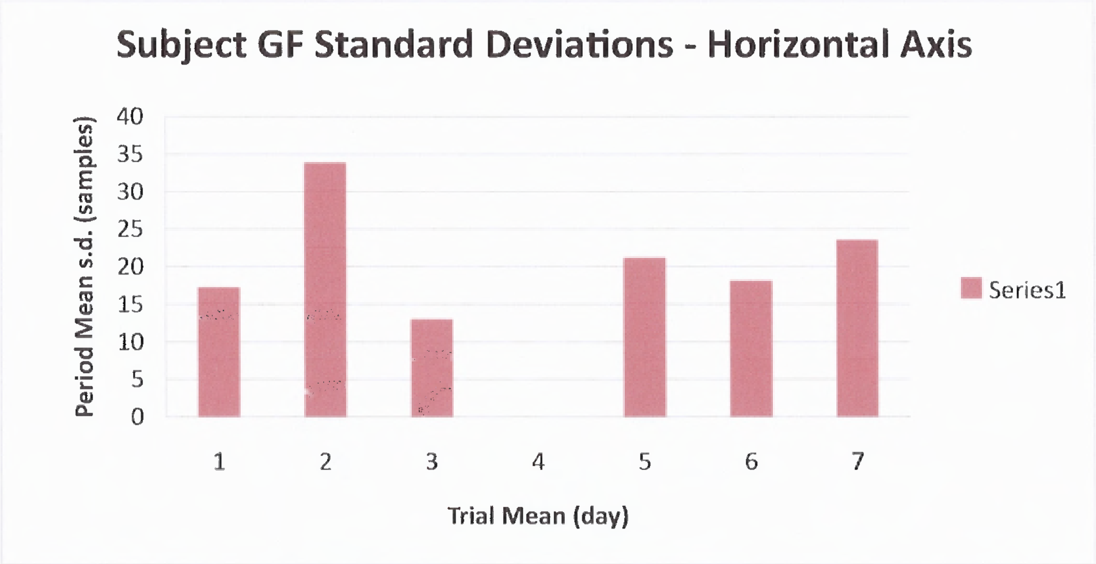


Figure 4.37 Subject GF Period Length Standard Deviations – Horizontal Axis Test.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

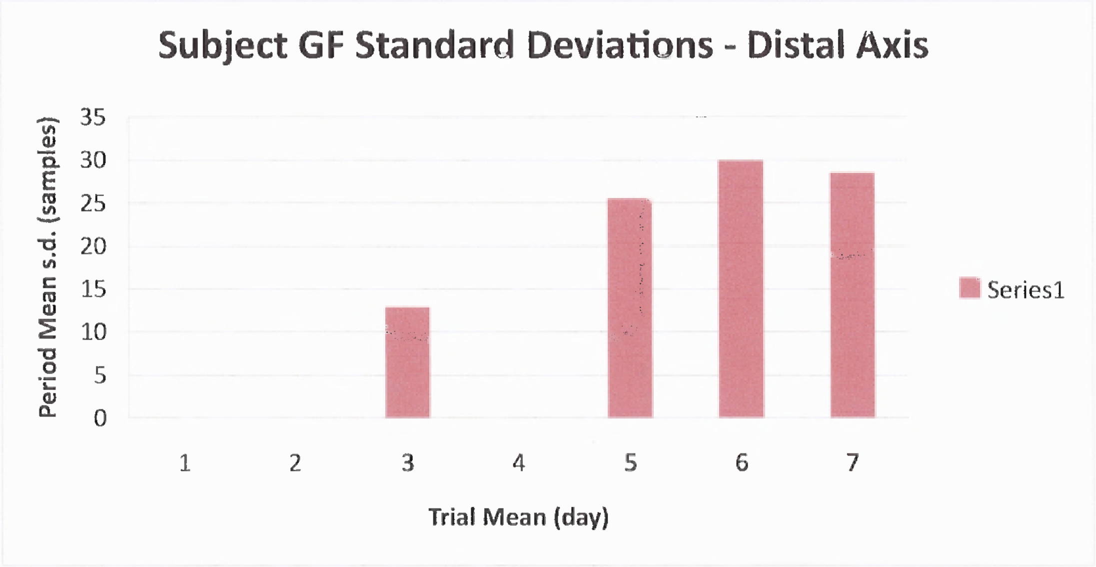


Figure 4.38 Subject GF Period Length Standard Deviations – Distal Axis Test.
Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

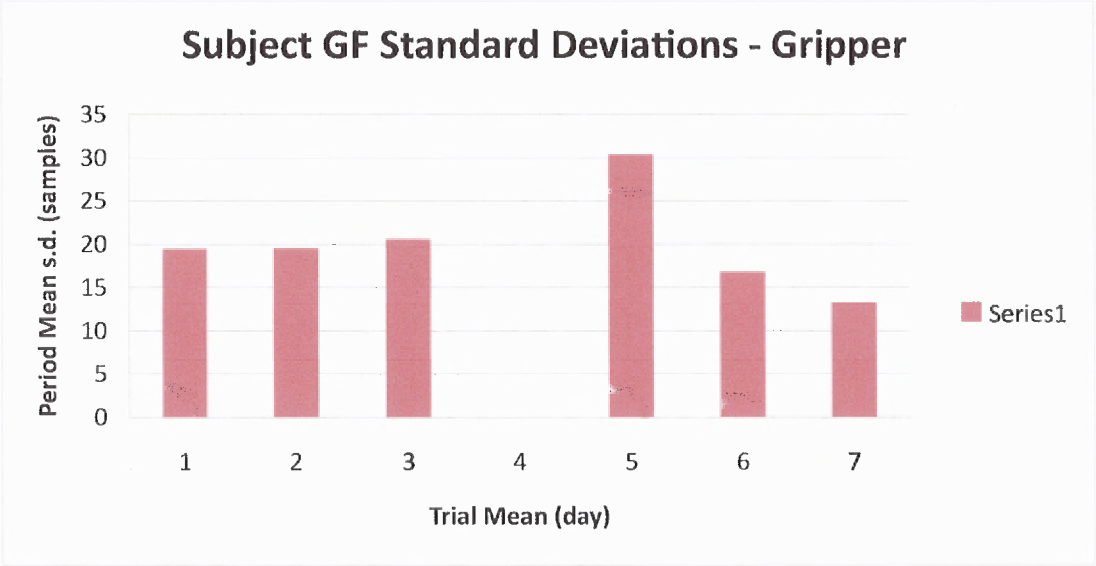


Figure 4.39 Subject GF Period Length Standard Deviations – Gripper Test.
Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

Both subjects had period means under 50 for the majority of their daily trial sessions, with the exceptions being Subject QQ's Distal Axis on Week 2, Day 1 and the

Gripper on Week 1, Day 3; and Subject GF's Horizontal Axis on Week 1, Day 2, and the Distal Axis on Week Day 1 and Day 3. This indicates that both subjects were able to switch between opposing directions in each axes frequently, but that they also gave misread facial expressions to the software.

Each also had specific challenges in their respective facial movements; subject QQ originally had difficulty in distinguishing between raise and lower eyebrows for the Vertical Axis Tests, and overcome this by moving her eyebrows to a Neutral expression once she noticed a specific movement occurring in the iARM. Subject GF initially needed more practice using Right Smirk compared to Left Smirk, and in later Distal Axis trials was only able to move in one specific direction.

In the case of subject QQ, the overall periodicity improved for both the Distal Axis and the Gripper. The period means for the Vertical and Horizontal Axes remained consistent between 30 and 50 samples, whilst those within the Distal Axis and Gripper had greater variation. In particular, the Gripper period means were lower than 35 in Week 2 of testing, indicating high responsiveness but also higher false readings from the user.

In the case of subject GF, he also maintained consistent results in both the Vertical Axis and the Horizontal Axis. The period means for the Vertical and Horizontal Axes improved in regularity despite the means being lower than 50. This indicates that subject was able to more consistently maintain a given period with applied training for the Vertical and Horizontal Axes. He had the greatest difficulty with the Distal Axis, being unable to perform one of the two directions within the first 2 days of week 1, but was significantly able to improve to the point where he could perform Distal Axis movements each day during Week 2. An anomaly in positioning is given for the Vertical Axis trials during week 1, day 3, and the Gripper trials of week 1 day 3; both display similar shapes to other trials in the same week and Test axis, but have approximately 33% of the positional data. This may be due to the sampling rate of the Transparent.exe program, which uses the PC's Operating System clock as a reference; if the PC has a large number of software programs or files open, then there may be slowdown. As this happened only on this specific testing day, the possibility of future occurrences can be decreased by minimizing the number of active programs when conducting trials.

The standard deviations of the period means of both subjects remained similar between the first and second weeks, indicating that variability may be independent of periodicity. However, for the majority of the Tests conducted, the standard deviations for each subject became more regular in the trials within the second week, indicating that they can be filtered or removed with sufficient training.

CHAPTER 5

CONCLUSION

Although the Emotiv EPOC^{TM} has difficulties of use compared to existing interfaces which use hand motion, whether as typing, movement of a mouse or positions of individual digits, it is a significant advance in terms of portability, robustness and user customization compared to existing medical EEGs. Furthermore, its usage as part of the larger trend of computer peripherals that make use of user movement, expressions and biofeedback is a sign of deepening the interaction between humans and computers for both medical and casual applications.

As EEG data requires filtering, there exists the possibility that the detected facial movements are in fact signals just below the skin surface to the user's facial muscles, making them a form of Electromyography or EMG. Unless the direct EEG input is available and decoded, this will require further confirmation. However, facial expressions have the most direct correspondence to brain activity compared to emotional states or movement intentions, as it involves translation of signals into physical activity instead of biofeedback in the case of Affectiv^{TM}, or purely planned movement for Cognitiv^{TM}. For the purpose of these tests, they can be considered virtually equivalent. Any movements deviating from the periodicity recorded are therefore not due to the subjects not performing the required facial expressions, but the difference in interpretation between the subjects' definition of a given expression, and the definition within Expressiv^{TM}. Although Expressiv proved the most intuitive for the subjects within this study, future experiments may combine more than 1 of the Suites to provide more specialized controls.

With the current Axis Tests, the Vertical Axis was the most consistent in terms of accuracy and intuitive user movement correspondence, horizontal Axis movement was also consistent, though by a smaller margin, Distal movement was more difficult due to a lack of direct correspondence between push/pull and facial expressions accepted in the current software, though movement of the lips may be a future possibility for development. Gripper movement was difficult initially because of the greater concentration needed for using Smile and Clench for the user.

The iARM itself proved more difficult to use than expected due to frequent needs for restarting due to internal software errors resulting from movement in specific positions. This may be due to the use of control software for the right-handed iARM being initially written for the left-handed version, but this was due to a left-handed iARM being unavailable. In future, it is unlikely that the iARM will be the robot arm of choice for EPOC^{TM} control due to this vulnerability. Because of the lack of delay in software and the greater reliability, the EPOC^{TM} has good development potential for multiple peripherals, as well as for existing and future simulations.

The EPOC^{TM} has proven to be an EEG equivalent to the first computer mouse, in that it provides a new human-computer interface for users with more direct movement translation, but requires development and testing to bring out its full potential. Although are currently less familiar to new users than conventional input peripherals, their current reliability, portability and end-user customization is far in advance of existing medical EEGs.

APPENDIX A

COMBINING THE CYBERGLOVE WITH A CYBERGRASP TO ALLOW FORCE FEEDBACK

The usage of the CyberGlove® allows for manipulation of virtual environments for Virtual Rehabilitation by direct finger movements. Unlike physical manipulation however, there is no tactile feedback for the user with a sensory-focused peripheral. Tactile feedback allows a more realistic simulation environment, both for training and for medical use such as tissue-equivalent objects and ultrasound training (Di Diodato, 2007), (Tahmasebi, 2008). To provide this, force-feedback peripherals such as the CyberGrasp™ by Immersion Corporation exist. In order to examine the future uses of the CyberGrasp™ for Virtual Rehabilitation in combination with sensory peripherals, the reconfigurability of an existing training program to the CyberGrasp™ was tested in the Spring of 2009.

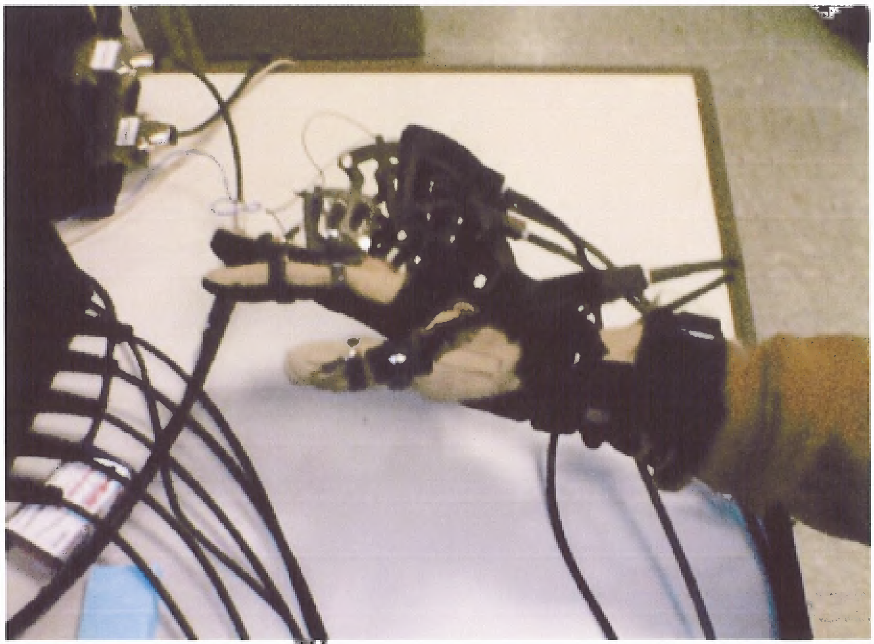


Figure A.1 The CyberGrasp™ haptic force feedback device, attached over a

CyberGlove®.

Source: Taken at NJIT BME Motor Control and Rehabilitation Lab.

The CyberGrasp™ is a force-feedback exoskeleton that attaches over a user's hands. It functions unidirectionally, in that it can exert force on the fingers to prevent them from closing, but prevent them from opening.

The program used to reconfigure for the CyberGrasp™ consisted of a cylinder placed upon a level grid. A virtual hand positioned in the models was able to move in 6-axes format to pass through the grid or move the cylinder. The original goal was to determine if contact between the virtual cylinder and the virtual hand could have force transmission from the CyberGrasp™ to the user's hand movements.

This was made difficult by a number of challenges in the previous program left to modify. The main difficulty is that the directions of the virtual hand did not correspond directly to the user's hand movements. Unlike training with the CyberGlove® Piano and Hummingbird simulations, the palm faces towards the screen instead of parallel to the floor or table, which obstructs the user's view and requires more effort to maintain. Although the X-Axis movements of 'left' and 'right' remain equivalent, the Y and Z-axes movements are not. This adds an unnecessary element of difficulty for the user or programmer.

Table A.1 List of CyberGrasp^{TM} Movement Directions

User Movement	User Axis	Virtual Movement	Virtual Axis
Into Screen	Z	Up	Y
Out of Screen	Z	Down	Y
Left	X	Left	X
Right	X	Right	X
Up	Y	Into Screen	Z
Down	Y	Out of Screen	Z

Collision detection is also difficult to apply and modify to the simulation. As described previously, the only position that the user can grasp the virtual cylinder is by moving the hand directly above. Because the CyberGrasp^{TM} can only apply forces to the fingers, this greatly limits the influence of the user's movements. Although it can be argued that the movement of the ends of the fingers will greatly determine the remaining positions of each of the segments, this approach reduces the fine motor control that the user can perform.

In the previous simulation, the hand is positioned with the palm down and the fingers facing away from the user, whilst the cylinder has its axis oriented vertically. This prevents the hand from grasping the cylinder from the x and y axes, which limits the direction of direct grasping to reaching the cylinder from directly above. Whilst this may be to focus the grasping direction consistently, the program itself does not contain instructions that clarify this.

The CyberGrasp^{TM} itself has a number of disadvantages that constrain its uses in Virtual Rehabilitation, even though the official workspace is given as being a 1 meter sphere from the Actuator Module. Whilst the glove itself is able to fit securely over a hand equipped with a CyberGlove®, the number of cables is significantly greater, in the case of 5 actuator tendons in total. Whilst these are aligned to avoid entanglement when bending or grasping, the hands are limited in rotation and reorientation at the wrist, requiring the user to maintain a hand position with the palms facing the ground surface. The CyberGrasp™, like the CyberGlove®, has left and right-handed versions, but require significantly more time to add and remove if the user is the only individual present during testing. In terms of portability, the CyberGrasp™, whilst having a mass of approximately 454 grams, is constrained by both the Actuator Module and the compressor that allows movement. The compressor itself is similar in volume and dimensions to a desktop PC, requiring a continuous power source and a multi-step activation and deactivation sequence, adding unwanted time to users and developers who intend to use it. The more recent GraspPack™ backpack does allow portability, but prevents users from being seated in any chair with a back due to the peripheral's protruding shape.

Whilst force feedback is useful in Virtual Rehabilitation, it is not essential to achieve precise, direct movement. Surgical robots such as the da Vinci System are an example of this, as whilst they cannot provide tactile feedback, the operator has access to visual data provided by the endoscopic camera. Because these are aligned, unlike traditional laproscopy, they allow a more streamlined sensory field for the surgeon.

Although the reconfiguration was unable to be completed during the Spring of 2009, it provided a valuable learning experience for Virtual Rehabilitation and comparative analysis. Working to reconfigure any form of simulation must be accessible to the end user, and the hardware must be portable and robust in order to maximize the time spent on training and improving movement skills, and minimizing the time spent on acclimating the user to the system.

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