A Precursor to a Balance Prosthesis via Vibrotactile Display

by
Jason Vivas

Submitted to the Department of Electrical Engineering and Computer Science
in partial fulfillment of the requirements for the degrees of
Bachelor of Science in Electrical Science and Engineering
and
Masters of Engineering in Electrical Science and Engineering
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
May 2001 [June 2001]

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Abstract

A joint effort between M.I.T., Massachusetts Eye & Ear Infirmary, and Draper Laboratory has developed a prototype of a balance prosthesis that uses electromagnetic vibrators, or tactors, to convey body tilt with respect to vertical.

Fourteen subjects, each with a vestibular disorder, were divided into two groups. Group 1 consisted of nine subjects who had compensated for their disorder and no longer experienced severe balance problems. Subjects in Group 2, on the other hand, had severe balance control deficiencies. Each subject was given two types of tests: sensory organization tests (SOT's), which measure the subject's ability to maintain quiet stance in the anterior/posterior (AP) direction while their vision and proprioception are compromised; and motor control tests (MCT's), which measure a subject's ability to regain their balance after a horizontal perturbation. SOT's were characterized by the subject's ability to increase their balance control with the balance prosthesis, i.e. decrease root mean square (RMS) body tilt. For MCT's, subjects were characterized by following parameters: maximum deflection after a perturbation, time after the deflection to stabilization, and RMS sway. These parameters were statistically examined to test their significance.

This thesis accomplishes the following:

1. It describes the development of hardware and software of a non-invasive balance prosthesis for patients with a vestibular disorder, none of which previously existed.
2. It describes a new test protocol that incorporated a training phase which greatly increased the effectiveness of the prosthesis and the reliability of the results.
3. It proves that the prosthesis, which provides knowledge of AP body tilt with respect to vertical, significantly increased AP balance control in quiet stance in vestibulopathic subjects. This result contradicts the inverted pendulum model

of body sway which requires two inputs for stabilization. The prosthesis stabilized vestibulopathic patients with only one signal, Θ.

4. It describes a significant improvement of balance of vestibulopathic subjects in response to applied disturbances. Although less dramatic than SOT, this result may be more applicable to activities of daily living.

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Acknowledgment I

I would first like to thank my advisors Gill Pratt, Conrad Wall, and Marc Weinberg for this wonderful opportunity. I cannot possibly convey to you the satisfaction I received from witnessing the dramatic improvement in balance control that subjects experienced, and knowing that I took part in developing the technology that made it all possible. For this and the wealth of knowledge you have given me, I am indeed indebted to you.

I would also like to thank Dave Balkwill- I would have been lost without your technical expertise; Erna Kentela- who made every test, and everyday for that matter, an enjoyable experience; and the rest of the staff at the vestibular lab- for your support and companionship.

This thesis not only marks an end to a wonderful learning experience, but also an end of a great journey. Allow me to describe this journey with the following lines:

For I have known them all already, known them all–
Have known the evenings, mornings, afternoons,
I have measured out my life with coffee spoons;[1]

I have realized that men labor under a mistake. The better part of the man is soon plowed into the soil for compost. By a seeming fate, commonly called necessity, they are employed, as it says in an old book, laying up treasures which moth and rust will corrupt and thieves break through and steal. It is a fool's life.[2]

Beauty is truth, truth beauty, that is all
Ye know on earth,and all ye need to know[3]

To those in the present and the past,
It has truly been the best of times and the worst of times.[4]

---

[1] *The Love Song of J. Alfred Prufrock*, T.S. Eliot

[2] **Walden**, Henry David Thoreau

[3] From *Ode To a Grecian Urn*, John Keats

[4] Modified from **A tale of Two Cities** Charles Dickens

To my family and friends,
it is to you that I dedicate this paper and all that it means to me.

ACKNOWLEDGMENT II

This thesis was prepared at the Charles Stark Draper Laboratory, Inc. and funded under the William F. Keck Foundation.

Publication of this thesis does not constitute approval by Draper of the sponsoring agency of the finding or conclusions contained herein. It is published for the exchange and stimulation of ideas.

(Author, Jason Vivas)

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Chapter 1

Introduction

From a systems controls standpoint, the body is an unstable system: 2/3 of its mass is located at 2/3 of its height above ground. Controlling this system, or maintaining balance, is required for everyday life and can potentially become a major problem if the balance system becomes corrupted by disease, injury or age. People with balance problems often complain of vertigo[1], lightheadedness, and unstable walking (gait). These symptoms tend to cause falls, which in turn may result in death, or an injury that burdens the patient, relative and/or society. As the average life expectancy increases, so does the number of elderly with a degenerated ability to control balance. In fact, 25% of elderly persons who receive a hip replacement after a fall die 6 months after surgery and of those who remain, 50% lose their ability to walk [1]. According to Statistics Canada, the number of deaths from elderly falls is almost equal to deaths from motor vehicle accidents in the 15-29 year population group [2]. Furthermore, over 50% of Americans will seek medical attention for dizziness at least once in their lifetime and the medical costs for those with chronic impairment exceed one billion dollars[1]. Some typical causes of loss of balance control are weak leg muscles, Epilepsy, Parkinson's disease, vestibular and brain-stem diseases, and unstable footing [3]. Balance disorders and their symptoms can lead to hazardous situations. A balance prosthesis may be effective in preventing falls by providing a

---

[1] Vertigo is when a person feels that they themselves and/or their surroundings are spinning.

frame of reference when one's own is compromised.

The balance prosthesis in this study is based on the idea of sensory substitution. That is, the prosthesis provides the information needed to stabilize the body via the somatosensory system instead of the balance system. This approach was proven in an earlier study on vestibulopathic subjects that explored the relationship between body sway and contact forces [4]. Subjects were asked to maintain balance in the tandem Romberg position[2], eyes either closed or open, under three conditions: no fingertip contact; *touch contact*, where the fingertip force (less than 0.98 N) cannot be used for support; and *force contact*, where the subjects could use any amount of force. Fingertip forces were measured both vertically and horizontally. The results showed that both touch and force contact help reduce body sway but surprisingly, touch contact was found to be just as effective as force contact. Furthermore, force measurements indicated that under force contact, body sway was in phase with fingertip forces, logically implying that the forces were used to correct body sway. On the other hand, fingertip forces in touch contact lead body sway by 250-300ms, suggesting that the fingertip forces provided the central nervous system (CNS) with position information but that reactions in body motion took up to 300 ms to appear [5].

A joint effort between M.I.T., the Massachusetts Eye & Ear Infirmary, and Draper Laboratory has developed a prototype balance prosthesis that uses tactile vibrators[3] (tactors) to create a reference frame that increases balance control. This reference frame comes in the form of one's body tilt, Θ, with respect to vertical. The prosthesis consists of three sections: the inertial instrumentation (which includes a gyroscope and accelerometer), a signal processor that calculates a tilt estimate from the instrumentation, and a vibrotactile display that conveys this measure of tilt to the patient.

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[2] The tandem Romberg position is where a person places one foot directly behind the other.

[3] Tactile vibrators are electro-magnetic vibrators made by Audiological Engineering, 35 Medford St., Somerville, MA, USA.

This thesis accomplishes the following:

1. It describes the development of hardware and software of a non-invasive balance prosthesis for patients with a vestibular disorder, none of which previously existed.
2. It describes a training phase which was incorporated into the testing protocol and greatly increased the effectiveness of the prosthesis and the reliability of the results.
3. It proves that the prosthesis, which provides knowledge of AP body orientation, significantly increased AP balance control in quiet stance in vestibulopathic subjects. This result contradicts the classic inverted pendulum model of body sway which requires two inputs for stabilization. The prosthesis stabilized vestibulopathic patients with only one signal, Θ.
4. It describes a significant improvement of balance of vestibulopathic subjects in response to applied disturbances. Although less dramatic than SOT, this result may be more applicable to activities of daily living.

Chapter 2

Background

2.1 Introduction to the Balance System

The balance system allows humans to go about daily activities by accomplishing the following tasks: 1) It provides the body's orientation relative to gravity and the direction, speed, and change of movement; 2) It is responsible for moving the eyes in a direction that is compensatory to subject motion, thus stabilizing images on the retina to prevent blurred vision and; 3) It maintains stable posture and dynamic movement, including balance correction responses that react to unexpected perturbations and balance stabilization responses that allow volitional control of movement [6]. Three major sensory systems are involved in accomplishing these tasks: vision, proprioception, and the vestibular system. In addition to helping people avoid physical objects, vision provides the CNS with information regarding the body's spatial orientation relative to the horizon.

The somatosensory system, or touch system, includes proprioception, which is elicited by mechanical displacements of muscles and joints. Proprioceptive receptors in the muscles and joints aid in balance control by determining the orientation of the body segments. Likewise, receptors in the feet can detect shear forces which can then be used to determine body position.

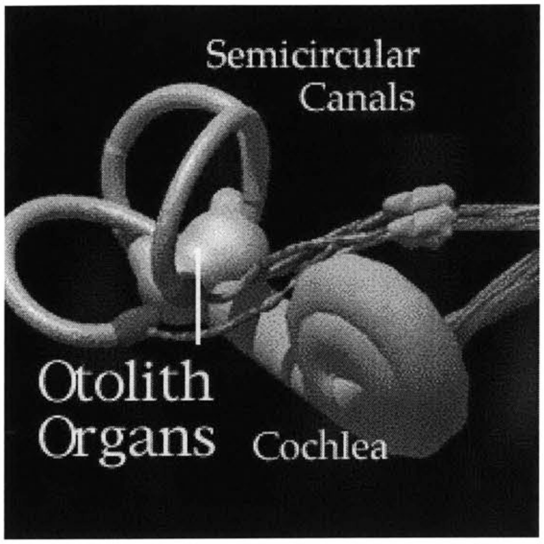

Figure 2-1: **The Vestibular End-Organs**

Lastly, located in the membranous labyrinth of the inner ear, are the vestibular end-organs, shown in Figure 2-1. They consist of two sets of structures, the semicircular canals and the otolith organs. Three semicircular canals lie in different planes which are nearly perpendicular to each other and measure angular acceleration. The otolith organs are responsible for detecting linear acceleration and determining the position of the head with respect to gravity. The membranous labyrinth is filled with a fluid called endolymph. An endolymph fluid filled ring forms the seismic elements of the semicircular canals. Head rotation causes endolymph to flow, which displaces hair bundles that extend from receptor cells. As a result, there is an alteration in nerve fiber signals that innervate the canals. The alteration is transmitted through the VIIIth cranial nerve to the brain enabling the CNS to detect the motion. The vestibular system plays an important role in balance control. The otolith organs work on a similar principle but use calcium carbonate crystals, called otoconia, for their seismic element. Whenever there is a conflict or lack of information from the visual or proprioceptive inputs, the vestibular system takes responsibility to orient the body [7].

2.2 Balance Control

The sensory inputs described above help the CNS correct errors in movement. That is, the CNS uses feed-back and feed-forward mechanisms to control motor systems. Feed-back involves comparing an actual signal- provided by sensory inputs, to a reference signal- the desired movement, and adjusting movement accordingly. Feed-forward mechanisms provide advance information to anticipate the information that is needed to complete a specific task. For example, when catching a ball, it is necessary to predict the ball's trajectory in order to correctly position the hand. Thus, feed-back and feed-forward mechanisms are important in controlling movement, and being deprived of sensory inputs that these mechanisms depend on would make daily activities very difficult.

This project is mainly concerned with movements associated with balance or postural control. Posture is defined as the overall position of the body in three dimensional space. Static and dynamic postural control involves three general control systems. The first is the myotic or deep tendon reflex. If stimulated by an external muscle pull, the myotic reflex regulates muscle forces that stabilize the respective joint. The second is the automatic muscle response, or functional stretch response. This response is activated by an external stimulation of the somatosensory system and provides for coordinated body segment movement. Finally, volitional movements are evoked by loss of balance, like during body sway. Like reflexes, they are extremely rapid, but unlike reflexes, these body stabilizing responses are learned and continuously refined with practice [6].

2.2.1 Body Sway and Quiet Stance

Controlling balance requires constant adjustment of one's center of mass (COM) to stay above the base of support, provided by the feet. Although the body is a dynamic system containing many moving segments, modeling the body will help us better understand and analyze balance and posture.

One important model of postural control was developed by Lewis Nashner and describes the body as an inverted pendulum. More specifically, the human body is represented by a mass constrained to rotate about a single pivot point, the ankles. The rotation, or body sway, is the summation of ankle joint torques and the torque resulting from gravity. Body sway is described in terms of Θ, the angle between the body and the vertical axis. In this model, control of forward and backward (anterior/posterior, AP) sway motion during quiet stance is the only degree of freedom [8]. Two inputs are needed to stabilize an inverted pendulum (maintain balance), either rate and position or rate and acceleration. In Nashner's model, the semicircular canals and otolith organs provide the CNS with rate and position that are then used to keep the COM above foot support.

Figure 2-2 shows the different forces associated with body sway. The vertical reaction force R located a distance d_1 from the ankle is equal and opposite to the body weight W located a distance d_2 from the ankle. Equation 2.1 describes the sway of the pendulum (the body) where Rd_1 and Wd_2 are moments, I is the moment of inertia of the pendulum, and α is angular acceleration.

$$I\alpha = Rd_1 - Wd_2 \tag{2.1}$$

Before describing AP sway, one must be able to differentiate between center of gravity (COG) and center of pressure (COP). COG is the vertical projection of the COM on the horizontal plane. The COM is the point in 3D space that represents the average mass of an object. Therefore, the COM of the body (located near the naval) would be the weighted average of the COM of each body segment. COP is independent of COG and represents the location of the weighted average of the vertical forces made against the ground by the feet [2]. Unlike COG, COP can be affected by, for example, ankle torques.

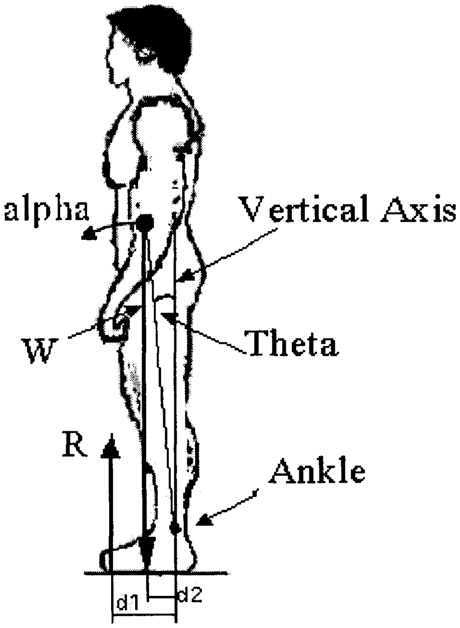

Figure 2-2: **Forces Associated with Body Sway**

Body sway occurs when Rd_1 and Wd_2 are unequal, resulting in an angle,Θ, between an imaginary line that connects the COM to the ankle and the vertical axis (as shown in Figure2-2). If $Wd_2 > Rd_1$, the body has a counterclockwise angular acceleration, α in Figure 2-2, and begins to tilt forward, thus moving the COG forward from the vertical axis. To stop this sway and keep the body from falling over, the body increases the COP until $Rd_1 > Wd_2$. At this point, the body creates an clockwise angular acceleration which tilts the body backwards, reversing the forward sway. The same sequence occurs in the opposite direction making it clear that body sway is the result of the COP moving anteriorly and posteriorly with respect to the COG in an effort to keep the COM over foot support [2].

2.2.2 Translations

Translations or perturbations to the body are a frequent occurrence in everyday activity. A pat on the shoulder or unstable footing are some common sources. The automatic muscle reflex is responsible for stabilizing the body after such a translation. This response is categorized by two strategies defined by the main joint around which the body rotates, namely the ankle strategy and the hip strategy [1]. The choice of strategy is made prior to any COM disturbance and depends on the environment and foot support. The hip strategy provides a greater restoring force than the ankle strategy and is therefore used in very unstable situations, such as when standing on a beam or on compressible surfaces. For larger support bases or slippery surfaces where friction is low, the ankle strategy is more appropriate. Proprioception is mainly responsible for initiating these balance restoring responses, not the vestibular system. Only when proprioception is compromised would the vestibular end-organs take control [6].

2.2.3 Summary

The CNS integrates vision, proprioception, and vestibular inputs to orient the body. It can be said then, that for quiet stance, the brain uses these signals to keep its COM over foot support. Balance control is one's ability to accomplish this effectively. Good balance control, therefore, can be characterized by small amounts of body sway and minimal movement of COP.

Although the Nashner's model of posture was used to analyze balance control in this project, it is not used to balance the body. The balance prosthesis described in the next chapter conveys only one signal, body tilt. Therefore, it does not attempt to increase balance control by stabilizing an inverted pendulum, which requires two feed-back signals.

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[1] There is also a step strategy that involves taking a step to widen ones base of support.

2.3 Balance Impairments

2.3.1 Vestibular Disorders

Vestibular disorders are the main cause of balance impairments. The ability to control balance can be compromised for a number of reasons, including but not limited to the following vestibular disorders:

Meniere's disease is defined as an increased pressure in the membranous labyrinth of the inner ear due to either over production or under absorption of inner ear fluids. This can damage the sensory hair cells that are necessary for the vestibular end-organs to transduce motion. Consequently, Meniere's disease is characterized by a triad of symptoms that includes tinitus, abrupt changes in hearing, and vertigo. There are medical and surgical treatments available for Meniere's disease. Medical treatment includes medication that stimulates blood circulation, anti-dizziness pills, and blood pressure pills.

Another disorder is when an acoustic neuroma (AN) develops on the VIIIth cranial nerve. AN is a benign schwannoma[2] that causes hearing loss, tinnitus, and vertigo. AN patients usually undergo surgery to remove the tumor, which may remove vestibular functions to the affected side due to the proximity of the vestibular nerve to the auditory nerve. As a result, the CNS receives only one signal, which translates into severe motion in one direction causing extreme vertigo.

Perilymphatic fistula is a disease where inner ear fluids leak through a perforation in the inner ear's membranous windows, causing fluctuations in vertigo and hearing loss. Treatment involves a surgery that *patches* the leak. This patch, however, is sometimes dislodged causing fluid to leak. Without the proper amount of endolymph, there is either none or false excitation of the vestibular hairs. As a result, perilym-

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[2] A schwannoma is a nerve cell tumor.

phatic fistula can lead to total loss of vestibular function [9].

2.3.2 Proprioceptive, and Other Disorders

Besides vestibular disorders, many other conditions may affect balance control, i.e. Parkinson's disease, old age, and Epilepsy. Some conditions, such as diabetes and large fiber neropathy, affect the proprioception directly. Large-fiber sensory neuropathy is a condition where the large fibers that carry proprioceptive and tactile information degenerate. The spinal cord no longer receives information from the muscle spindles and these patients are unable to accomplish tendon reflexes. Unless they can see their limbs, these patients cannot sense their position or detect the motion of their joints [7].

2.3.3 Compensation

The CNS has the remarkable trait of being able to compensate for impairments. For example, a patient with a unilateral vestibular lesion[3] can recover enough to resume normal life. One possible explanation is that the CNS changes its responses to familiar stimuli, thereby adjusting to one vestibular input instead of two. Moreover, the CNS is able to compensate for sensory system disorders by relying more heavily on the other functional systems. Another explanation involves sensory substitution, or acquiring the needed balance information from one or both of the other systems involved in balance [6]. The prosthesis takes advantage of the latter to help those with a balance impairment.

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[3] A unilateral vestibular lesion is a vestibular disorder associated with only one ear.

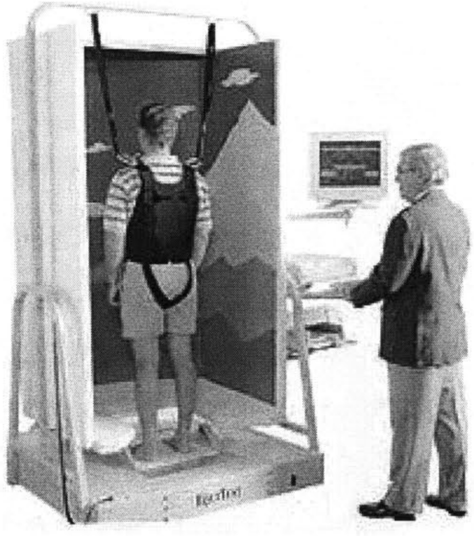

Figure 2-3: **The Equitest.**

2.4 Measuring Balance

Body sway can be measured various ways. The most common technique is to have a subject stand on a forceplate. The forceplate contains a number of force transducers that are summed to find a subject's COP. Another method is to attach various light emitting diodes (LED's) to body segments. A sensor detects LED movement, and thus body segment movement, from which body tilt can be calculated.

Because the visual, proprioceptive, and vestibular systems are partially redundant, researchers have developed dynamic tests to pinpoint abnormalities in sensory systems. The Equitest, or computerized dynamic posturography, is one such machine (See Figure 2-3). It analyzes a patient's ability to maintain or regain balance under a variety of conditions. Patients stand on a forceplate that can move in a plane parallel to the floor or pitch about an axis that is co-linear with the ankle joint. The subject's field of vision is encompassed by a visual enclosure that can also pitch about an axis. Allowing the forceplate and/or enclosure to pitch is called sway-referencing. This is accomplished by feeding the COP from the forceplate to a controller that tilts the platform and/or enclosure so that the subject's body is always perpendicular to their feet. Therefore, a subject's proprioceptive input can be distorted by sway-refrencing the forceplate and their visual input can be either denied by asking the patients to keep their eyes closed, or it can be distorted by sway referencing the enclosure. Essentially, the platform removes or distorts the visual and proprioceptive inputs, forcing the patient to rely on their vestibular system for stability. Vestibulopathic subjects have to rely more heavily upon the senses of vision and proprioception than do normals. When they are deprived of the latter, subjects are left with minimal balance control. In this project, the void of balance information will be filled with vibrotactile information [11].

Two main types of tests can be administered on the Equitest: sensory organization tests (SOT's) and motor control tests (MCT's). SOT's require the subjects to maintain balance to the best of their ability for 20 seconds under various conditions. SOT under condition 5 (SOT 5) requires subjects to stand with their eyes closed while the forceplate is sway referenced. SOT 6 is both visually referenced and sway referenced so that both the enclosure and forceplate tilt with the patient [11]. SOT's were used to gain insight on how the prosthesis affects balance control in quiet stance in patients with vestibular disorders.

MCT's consists of three randomly timed linear translations of the forceplate in a horizontal plane. These perturbations can be either forward or backward can vary in strength. A small translation is enough force to tilt the body 0.7°, a medium translation is enough to tilt the body 1.8°, and large translations, 3.2°. Subjects can stand with their eyes either open or closed and are asked to stabilize themselves as quickly as possible [11]. MCT's were used to determine if a tactile display can aid subjects in recovering from COM perturbations. MCT's will gauge whether the information provided by the prosthesis has the potential of being useful for stabilizing a subject during COM translations.

Another advantage of using the Equitest is its training capabilities. With the aid of Balance Master software[4], a patients COP (represented by a small figure) is displayed on a flat screen that is attached to the Equitest's visual enclosure directly in front of the patient. The display also presents the patient with a series of targets. When a training session begins, targets are individually activated (indicated by a change of color) for a brief period of time, and patients are asked to tilt their body so that the figure representing their COP is superimposed on the activated target. This feature will be an integral part of the testing protocol described in Section 4.2.

2.5 Applications

There are several applications for a balance prosthesis. The main focus, however, is to assist people with an incomplete balance system, like those who suffer from any of the disorders described in Section 2.3. In addition to their uncomfortable and inconvenient state, these vestibulopathic patients run the risk of being involved in an accident because of their disorder. Most patients learn to compensate for their disorder and live relatively normal lives due to the redundant nature of the balance system. However, the risk of falling can arise when any one of the systems involved in compensation are missing and/or distorted. A balance prosthesis would provide these patients with the information needed to prevent falls, in any challenging situation where balance is compromised.

After a destructive surgery, where the acoustic neuroma is removed, patients feel extreme vertigo and are bedridden for a lengthy period of time, making the recovery process a very long and arduous one. This dilemma stems from the fact that the CNS is no longer receiving vestibular information from the operated side. The balance prosthesis could speed up recovery by helping these patients adjust to their condition.

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[4] Balance Master software is a product of NeuroCom International, Clackmas, Oregon, USA.

Chapter 3

The Balance Prosthesis

3.1 Components

The balance prosthesis contains three major sections: inertial instrumentation, a digital signal processor, and a vibrotactile display. (See Figure 3-1 for an overview on the flow of signals.)

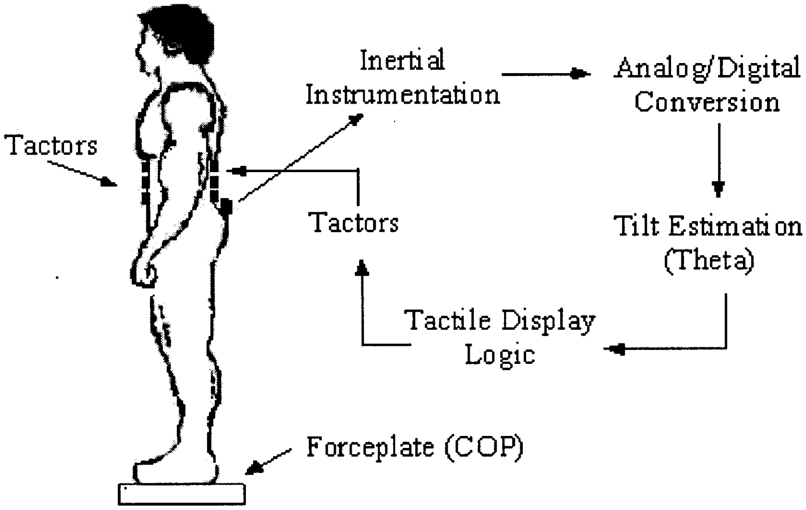


Figure 3-1: **Signal Flow Diagram**

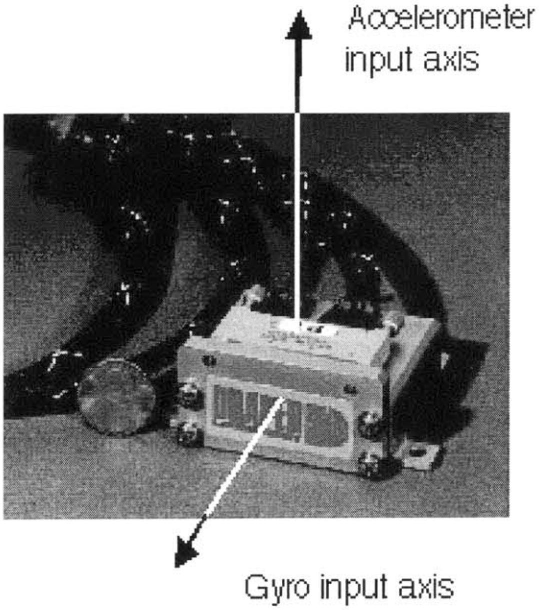


Figure 3-2: **Inertial Instrumentation [10].**

3.1.1 Inertial Instrumentation

In the fingertip experiment, touch contact cues provided subjects with an orientation reference that reduced their body sway. Recall that touch contact involved touching a stationary stand with a finger at mechanically non-supportive force levels. Body movement was determined by the shear frictional forces between the stand and the finger [5]. In this experiment, the inertial instrumentation (Draper Laboratory[1] part number 384521) shown in Figure 3-2 provides body movement information using micro-mechanical devices. These devices were developed at Draper Laboratory and include a gyroscope (Draper Laboratory Model TFG-13) and an accelerometer (Draper Laboratory Product Two). Signals from the instrumentation are passed through a filter box (Draper Laboratory part number 383895) and into a digital to analog converter (DAC) to be processed. The instrumentation is secured to the body and will be used to provide its possessor with an estimation of their body tilt, Θ.

---

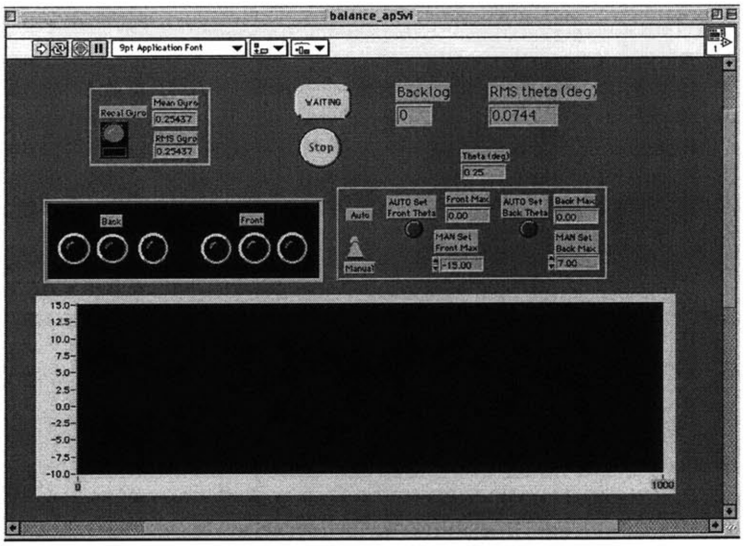
[1] The Charles Stark Draper Laboratory, 555 Technology Square, Cambridge, MA, 02139, USA

Please see [10] for complete details on the micro-mechanical devices and their signals.

3.1.2 Signal Processing

Tilt angle is actually calculated by a computer algorithm. Neither the gyroscope nor accelerometer alone can accurately provide a measure of tilt over the required frequency range [10]. Section 3.3.3 gives an overview of the signal processing in this experiment.

The user interface was designed using LabView software on a portable Powerbook computer. Not only does the software accomplish the real time signal processing needed to convert the instrumentation signals into a tilt estimate, but it also allows the test-taker to adjust many parameters affecting filter performance, tactor firing ranges, and data collection. Figure 3-3 shows the main display of the LabView program which can present any parameter involved in the experiment, including Θ, COP, and tactor firing modes.



Mean Gyro 0.25437
RMS Gyro 0.25437
Backlog 0
RMS theta (deg) 0.0744
Theta (deg) 0.25
AUTO Set Front Theta
Front Max 0.00
MAN Set Front Max -15.00
AUTO Set Back Theta
Back Max 0.00
MAN Set Back Max 7.00

Figure 3-3: **LabView User Interface.** The interface allows one to monitor any parameter involved in the experiment, including Θ, COP, and tactor firing modes.

3.1.3 Vibrotactile Display

A vibrotactile display consists of small tactile vibrators called tactors that were developed by Audiological Engineering[2]. Tactors, three of which are shown in Figure 3-4, are electro-magnetic vibrators that can be driven in the 200 to 400 Hz range. The use of tactile stimulation to replace diseased or lost senses is not a new idea. Other areas include tactile speech encoders developed for the deaf and also tactile displays for vision prostheses [13]. Furthermore, much research has been done on skin properties that prove that a tactile display is useful [15, 16].

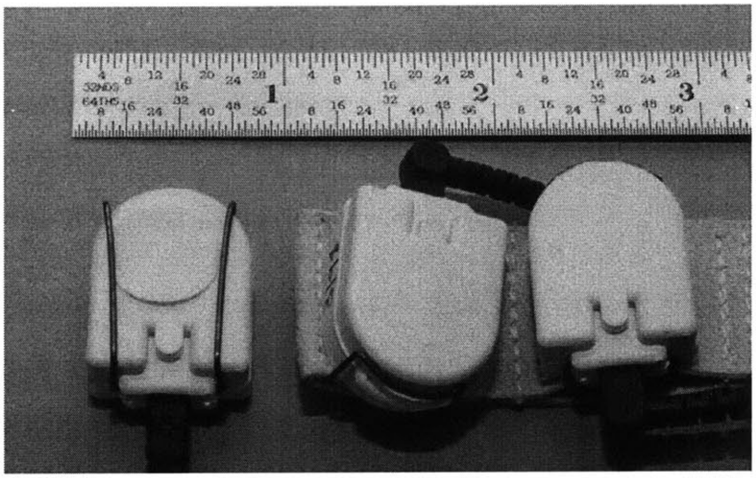


Figure 3-4: **Vibrating Tactors [10].**

The prosthesis will use a vibrotactile display to convey Θ. Tactors are fired using a voltage signal whose amplitude[3] and frequency are digitally programmed in the Powerbook. The number of tactors and their configuration depends on where they will be placed on the body and on the type of information to be conveyed. Two methods of encoding information are spatial coding and pulse interval coding. Spatial coding is best explained using an analogy of climbing a ladder, where altitude corresponds to Θ and each step on the ladder corresponds to a tactor level. The

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[2] Audiological Engineering, 35 Medford St., Somerville, MA, USA, 800-283-4601

[3] All input and output voltage signals are less than 5 V.

higher one's altitude, or the more one tilts, the higher the step is that one stands on, or the higher the tactor level. A second method, pulse interval coding involves rate modulating the tilt signal, where an increase in Θ is matched with an increase in pulse rate [18].

3.2 Previous Experiments & Configurations

Normal Subjects This thesis is a continuation of a previous study where, similar to the fingertip experiment, subjects with no balance impairment were asked to maintain stable posture in the Tandem Romberg position. The subjects wore the instrumentation on the side of the head and medio-lateral (ML) tilt information was fed back to them via the vibrotactile display. One tactor was placed on each shoulder and were fired by way of pulse interval coding. Two additional columns of tactors were placed on either side of the trunk and were fired by way of spatial coding. Subjects were tested under four conditions: no balance aids, tilt information via shoulder tactors (pulse interval coding), tilt information using side tactors (spatial coding), and light touch (similar to that of the fingertip experiment, see Section 1.1). The following three parameters were taken from each test: root mean square[4] (RMS) Θ, RMS center of pressure displacement (CPD), and fraction out of threshold (FOT)[5]. The following summarizes some key points and results from the experiment [14].

- There was a 35% reduction in RMS head tilt and a 33% reduction in center of pressure displacement (CPD) with side tactors when compared with no balance aids. In addition, there was a 48% reduction in RMS head tilt and a 59% reduction in CPD for light touch when compared with no balance aids. Therefore, the test proved that tilt information via vibrotactile display can reduce head sway.

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[4] RMS, or root mean square, is equal to the square root of the variance of a vector.

[5] FOT is the fraction of time for which head tilt exceeded +/- 0.5 degrees.

- Light touch had an overall lower RMS Θ and RMS CPD when compared to the balance prosthesis. Two reasons can account for this result. First, reactions to light fingertip touch may be faster than the encoded stimulation provided by the prosthesis, resulting in a more efficient and effective control of balance. Second, light touch gives the CNS information about the body with respect to a fixed reference while the prosthesis only gave head tilt.
- FOT was higher for light touch than with the prosthesis, which contradicts the previous result. One explanation could be that the prosthesis conveyed head tilt information, not COP information. As a result, patients were in a better position to stabilize their head when the prosthesis was activated and may have concentrated on keeping the head stable rather than the entire body.
- Side tactors reduced body sway to a greater extent than did the shoulder tactors.

3.2.1 Vestibularly Impaired Subjects

There was a second experiment that involved subjects with vestibular disorders. The same test configuration and protocol from the previous experiment was used except that the tilt estimate was calculated with a Kalman filter. The results of this test were inconclusive and the following are some explanations [19]:

- The Kalman filter used to calculate Θ may have been flawed and/or inappropriate for the context of the experiment. As a result, subjects did not believe the tilt signal was reliable.
- Training was insufficient to develop skills or trust in balance prosthesis.
- Stabilizing head tilt was not sufficient to stabilize posture.
- Subjects could not feel tactor display or understand coding.

3.3 Current Experiment & Configuration

To further develop the prosthesis, a second generation prototype and testing protocol was designed with the following goal: effectively increase AP balance control in patients suffering from a vestibular disorder. To accomplish this, the test configuration and protocol underwent significant changes.

3.3.1 Test Configuration

The new experiment took place on the Equitest platform which measures AP balance control. Therefore, the instrumentation had to be moved from the side of the body to either the front or the back. It was then decided to place the instrumentation on the lower back of the subjects as opposed to the head. This was done for two reasons. The previous experiment showed that head tilt may not necessarily be the best indicator of body orientation. This move is further justified by a previous experiment that found that COM movement is highly correlated to lower back movement [20]. Therefore, this configuration will directly convey COM movement information to the subject. The success of the prosthesis lies in whether or not the CNS can use this information to minimizing body sway. This is very plausible, because, as described in Section 2.1.1, balance control is the ability to maintain ones COM over a support base. Direct knowledge of COM movement should aid in its control.

This move highlights an important distinction. This project describes a balance prosthesis, not necessarily a vestibular prosthesis. Although the instrumentation provided similar information and was placed in a similar location to that of the vestibular end-organs, the prosthesis and the end-organs do not accomplish the same task. The end-organs convey head position with respect to gravity and also head acceleration while the prosthesis conveys body tilt.

3.3.2 Equipment Configuration

Figure 3-5 is a wiring schematic that shows how the various components in the experiment interconnect. Forceplate voltage signals do not originate directly from the force transducers on the Equitest. The raw transducer voltages are calibrated by the Equitest Signal Conditioning box. The five forceplate voltages are right front (RF), left front (LF), right back (RB), left back (LB), shear, and a synchronization signal, which contains the test timing information. These signals along with the instrumentation signals are fed into a Draper filter box and digitized using a National Instruments DAQ-1200 card. A Macintosh G3 Powerbook containing the LabView software then handles all of the signal processing. The LabView program uses the instrumentation signals to calculate a tilt estimate that is passed through tactor logic, which determines the correct row of tactors to be fired. The computer outputs this signal through tactor drivers, located in the Draper Filter Box, and finally fires the appropriate tactors. The Powerbook saves the data of each test run onto its hard-drive. After all test runs are completed, the raw data is transfered to desktop G3 Macintosh. Matlab scripts are responsible for extracting the necessary information and for making the necessary calculations (See Appendix F for Matlab scripts).

3.3.3 Signal Processing

Instead of using a Kalman filter, a lowpass and high pass filter combination was used to estimate Θ. The voltage output of the accelerometer is described in Equation 3.2 and 3.2, where L is the height of the instrumentation, g is the gravitational constant, $\ddot{\Theta}$ is acceleration, Ω_h is the horizontal acceleration of the pendulum pivot (equal to zero in this experiment) [10]. The accelerometer is detecting linear acceleration that is tangential to the body axis (high frequency component) and g $\sin(\Theta)$ (the low frequency component). This signal is low pass filtered to preserve the low frequency tilt information.

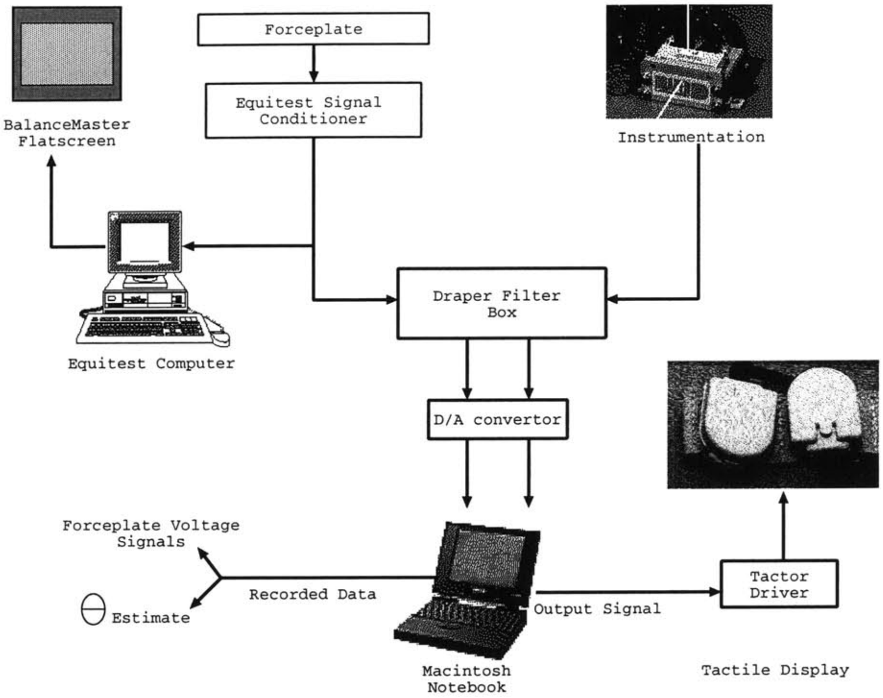

Figure 3-5: **Wiring Configuration.**

$$V_A = S_A \Omega + B_A \tag{3.1}$$

$$\Omega = g \sin \Theta - L \ddot{\Theta} + \Omega_h \tag{3.2}$$

The voltage output of the gyroscope is described in Equation 3.3, where S_G is the scaling factor, $\dot{\Theta}$ is angular rate, and B_G is the bias. The gyroscope signal detects angular rate in the AP direction and must be integrated to acquire a Θ estimate. This integration, however, increases the bias and would cause drift. Therefore, the signal is first high pass filtered and then integrated.

$$V_G = S_G \dot{\Theta} + B_G \tag{3.3}$$

To obtain a good estimate over the necessary frequencies, the accelerometer is

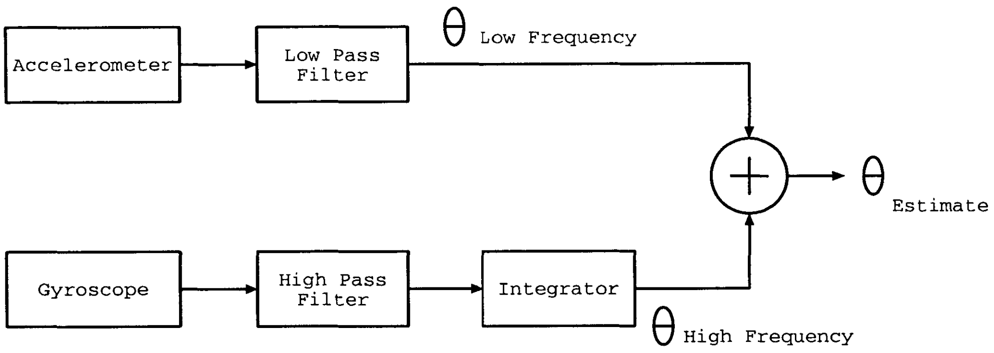

Figure 3-6: **Signal Processing Block Diagram.**

used to provide low frequency estimates and is then combined with the gyro high frequency tilt to form a final tilt estimate [10]. Figure 3-6 displays a block diagram of this system. The system requires an initial calibration which involves holding the instrumentation vertical for one second and adjusting the gyro coefficients to compensate for any offset.

3.3.4 Vibrotactile Display

The vibrotactile display was also reconfigured. The new display consists of two parallel columns of three vibrating tactors located on the lower portion of the stomach and back. The surface area along the spine varied too greatly from person to person to allow a single column to be used. Therefore, two columns were placed on either side of the spine and stomach to make things symmetrical. Each row of tactors represents a tilt angle range that is determined by first establishing the maximum forward and backward tilt. This allows the prosthesis to accommodate various degrees of balance control. A short, elderly person may not be able to tilt to the same degree as a taller, younger person, and would thus require different firing ranges. Also, the ability to customize the firing ranges will account for the fact that people can lean forward farther than they can lean backward. See Figure 3-7 for a graphical representation of a customized spatial coding scheme. Typically, subjects had a maximum

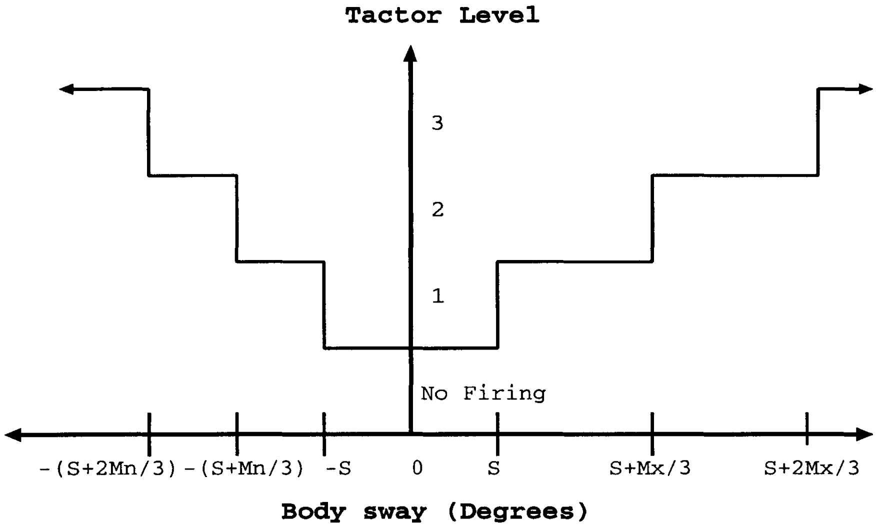

Figure 3-7: **Tactor Firing Configuration.** The x axis is Θ (degrees). Positive Θ indicates forward sway and negative Θ indicated backward sway. *S* defines the stable zone where the tactors will not fire. *Mx* is the maximum forward tilt minus *S* degrees and *Mn* is the maximum backward tilt minus *S* degrees.

forward tilt between 8° and 10° and a maximum backward tilt between 6° and 8°. To accommodate normal sway, a threshold of 1° to either side of the subject's normal upright position is established in which no tactors are fired [14].This *no firing zone* is indicated with an S in Figure 3-7. Moreover, the tactors are placed in an elastic vest that ensures adequate contact with the skin. Good contact is crucial to a subject's ability to distinguish between tactor rows.

Chapter 4

Experimental Methods

4.1 Subject Pool

Fourteen subjects, each with a vestibular disorder, were recruited and divided into two groups, depending on their balance control. Subjects in Group 1 were recruited from the Acoustic Neuroma Association (ANA), and have had their acoustic neuroma removed. These subjects have compensated for their unilateral loss of vestibular function and no longer experience severe balance problems. Group 2 are subjects recruited from the Massachusetts Eye & Ear Infirmary (MEEI). Unlike Group 1, these subjects have a severe balance impairment. Subjects for Group 2 were recruited based on the following criteria: the subjects had to have a balance disorders that caused them to score below average on SOT 5 and SOT 6 but were otherwise in good general health (See Section 2.4 for SOT details).

4.2 Testing Protocol

The protocol was approved by the Human Subjects Committee at the Massachusetts Eye & Ear Infirmary, the Institute Review Board at Massachusetts General Hospital, and the Committee on the Use of Humans as Experimental Subjects at the Massachusetts Institute of Technology.

Each experiment is divided into four main phases. The first phase involves recording subject medical data and familiarizing the subject with the experiment. All subjects, except for subject 7, have undergone a battery of vestibular tests at one point or another. These tests include electro-nystagmagraphy (ENG), rotations about a vertical axis, and computerized dynamic posturography (CDP). The results from these tests give insight as to how well a subject is able to control their balance. In addition, subjective data was recorded in the form of a Function Level Evaluation Test. This survey originates from the American Academy of Otolaryngology- Head and Neck Surgery (AAOHNS) and was designed specifically for people with Meniere's disease. It serves as a good indicator as to how a subject's balance disorder affects their daily life. The Function Level Test is scored on a scale between 1 and 6, where a score of 6 means the subject's disorder inhibits normal activity to the maximum degree [12]. The subjects were then outfitted with the prosthesis and asked to stand on the Equitest where they are introduced to the tactile vibrations and the tactor firing ranges are set. To set these ranges, subjects are asked to lean forward and backward until they feel that they are about to fall in that respective direction. Then the angles between the *no firing zone* and the respective maxima are equally divided into three ranges[1]. This customizes the prosthesis to accommodate all levels of balance control.

The second phase, or training phase, uses the Equitest System and BalanceMaster software to meet the following goals: to familiarize the subjects the Equitest tests, to *teach* the subjects the mechanics of body sway, and to help them develop trust the information given to them by the prosthesis. This is an integral part of a successful experiment. Although spatial coding is intuitive, the subjects required a period of time to learn how to use the tactile information. Subjects were asked to undergo the training scenario described in Section 2.4 under four conditions: eyes open, with and without the prosthesis activated, and then with eyes closed, with and without the prosthesis activated.

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[1] This is done automatically by a LabView program.

Just to reiterate, the brain naturally calculates its orientation using any combination of the balance inputs. Loss of balance occurs when these signals are distorted and/or missing. These subjects have varying levels of vestibular disorders and rely on other sensory inputs to maintain balance. The tests involved in the experiment are designed specifically to remove those sensory inputs that they depend so heavily. The balance prosthesis is designed to provide a means of balance control under such conditions, but subjects need time to understand and trust this information. The purpose of the training session is to develop this *relationship* between the prosthesis and the subject.

After the subject has had sufficient time to understand both the prosthesis and the Equitest, the flat-screen was turned off and the third, or testing phase, of the study began. Three types of tests (SOT 5, SOT 6, and MCT) were administered in sets of five, each containing three runs (See Section 2.4 for test details). Table 4.1 shows a typical testing regiment, where the set number also represents the order in which tests were administered. Test runs were given in groups of three and alternated from No Tactors (NT) to With Tactors (WT). This was done to address the learning curve. As subjects repeat the same task, they are expected to improve. Interweaving tests with and without an activated prosthesis will help distinguish between learning improvements and improvements caused by the prosthesis. Sets 1 through 4 are the minimum number of tests needed to complete each testing experiment. However, depending a subject's physical strength and ability, more tests were often added, particularly SOT's. This accounts for added SOT's in Sets 5 and 6. Each set will produce fifteen runs of data (Recall that each MCT involves three randomly spaced runs).

The final phase of the experiment involved a second survey that recorded each subject's opinion on the usefulness of the prosthesis. This *usefulness* score was based on a scale of 1 to 10. A score of 1 means that the subject felt that the prosthesis was of no use in keeping their balance during tests, while a score of 10 means that the

Set Number	Test Type	Tactor Signal	Iterations
1	SOT 5	NT WT NT WT NT	3 EACH
2	SOT 6	NT WT NT WT NT	3 EACH
3	MCT Backward Medium	NT WT NT WT NT	1 EACH
4	MCT Backward Large	NT WT NT WT NT	1 EACH
5	SOT 5	NT WT NT WT NT	3 EACH
6	SOT 6	NT WT NT WT NT	3 EACH

Table 4.1: **Test Protocol.** BM are Backward Medium perturbations, BL are Backward Large perturbations, NT means that no tactors are activated, and WT means the subject is with tactors activated.

subject believed that the prosthesis was very useful in maintaining balance.

4.3 Data Analysis

4.3.1 Subjective Data

Subjective data recorded in the pre-test phase was evaluated to determine the subject's medical status and current balance control ability. The two most informative results from the testing battery scores described above are the SOT overall score and an MCT overall score. The SOT overall score stems from the subject's performance from all six SOT conditions of the Equitest. A person with a normal balance system would on average receive an SOT overall score of 72. The higher the score, the better the subject's ability to control his/her balance. The MCT overall score is a measure of a subject's ability to initiate a response after a horizontal perturbation. In other words, it is an indicator of the subject's ability to react to a horizontal translation.

On average, a normal balance system would receive an MCT overall score of 158. In this case, the lower the score the better the subject's ability to initiate a response. Both scores take the subjects height and age under consideration [11]. The post-test data determined the extent to which subjects felt they benefited from the prosthesis. It gives us their opinion on whether they believed that the prosthesis could be useful to them.

4.3.2 Objective Data

During the experiment, the subjects wore the prosthesis and stood on the Equitest platform. The computer recorded data from both the instrumentation and the platform's forceplate. These signals were used to obtain a Θ estimate (degrees) and a COP measurement (inches), respectively.

Because the platform is sway-referenced during SOT's, only Θ will be analyzed. For those subjects who lost complete control of their balance and were unable to complete the test run, the test run was marked as a fall. To accommodate this in the analysis, the reciprocal of the RMS Θ was calculated and falls were given a value of zero. The Θ and COP signals, both of which show a similar form, will be used to evaluate MCT's. Each MCT curve consists of a sharp increase in Θ or COP as the body leans at the onset of a translation. The body reaches a peak tilt and then there is a recovery period. From the SOT and MCT signals, the following parameters were calculated:

- 1/(RMS Θ) (degrees) for SOT 5 and SOT 6.
- Peak Deflection, both Θ (degrees) and COP (inches), for MCT Back Medium and Back Large perturbations.
- Recovery Time (seconds), both Θ and COP, for MCT Back Medium and Back Large perturbations. This measurement is the amount of time it takes the subject to return to and stay within the no firing zone of $\pm1.0°$ after the peak deflection.

- RMS Θ (Degrees) and RMS COP (inches), for MCT Back Medium and Back Large perturbations.

These parameters were statistically examined using a one-tailed, matched paired t-test, by subject and by group, to determine if the balance prosthesis was effective. A matched paired t-test is used when the a particular subject in an experiment is tested under two different conditions. It is the difference between scores in conditions that is examined. Using SOT scores as an example, 1/(RMS Θ) under WT is subtracted from 1/(RMS Θ) under NT. If the prosthesis is effective, this difference should be a negative number. The paired t-test will decide if the differences are statistically significant [17]. The SOT data that was analyzed came from sets 1, 2, 5, 6 in Table 4.1. Data from the No Tactor (NT) condition was compared to data from the With Tactor (WT) condition. For most subjects, each set consisted of three NT sets and two WT sets, resulting in missing data points. The paired t-test was accomplished by taking the first two NT parameters and subtracting them by the two WT parameters. MCT data was acquired in a similar manner. The results were not critically dependent on which pairs were selected. Group data was analyzed in a two step process. All available paired differences for each subject in group were combined and then tested for statistical significance. Two sets of Matlab scripts, one for SOT data and one for MCT data, are initiated and are responsible for extracting the appropriate parameters and performing the statistical analysis (See Appendix F for Matlab scripts).

Chapter 5

Results & Discussions

5.1 Results

5.1.1 Introduction

Fourteen vestibulopathic subjects were tested. Surveys and medical histories were recorded to assess their degree of balance control. Subjects were then given two types of tests that recorded their balance control during quiet stance and in response to a perturbation. Finally, an additional survey gauged how useful they perceived the prosthesis to be. The following sections will outline the results of these examinations.

5.1.2 Subjective Data: Pre-Test

All subjects were in good physical health. Subjects in Group 1 have compensated for their unilateral loss of vestibular function and no longer experience severe balance problems. However, they did share some similar experiences. For example, these subjects had difficulty walking in the dark and up and down stairs. They also experienced frequent collisions with stationary objects. It follows then, that the mean SOT overall score for Group 1 is 71.6 (borderline for normals), the mean MCT overall score of 146.9, and the mean Function Level score of 1.9. Table 5.1 displays each subject's balance control ability. To summarize, these subjects were minimally affected by their

SUBJECT	AGE	SOT OVERALL SCORE	MCT OVERALL SCORE	FUNCTION LEVEL SCORE
1	27	72	139	3
2	64	79	146	3
3	56	73	148	1
4	58	72	150	2
6	56	70	155	0
8	58	69	155	3
11	40	70	129	1
13	68	68	146	3
14	31	71	154	2
MEAN	50.9	71.6	146.9	2
ST DEV	14.6	3.2	8.5	1.1

Table 5.1: **Group 1 Balance Control Ability** A high SOT Overall score indicates good balance control during quiet stance, while a high MCT Overall score indicates an inability to initiate a response after a perturbation. High Function Level score means that the respective subject's balance disorder affects their daily life to a high degree.

vestibular disorder and were physically able to complete the tests.

Subjects in Group 2, on the other hand, had severe balance problems, especially when their vision was impaired. One subject shared an experience that clearly shows the extent to which a balance disorder can affect daily life. This subject stayed outside after the sun had gone down and was forced to crawl back home, unable to walk due to the lack of visual input. Group 2 has mean SOT overall score of 51, a mean MCT overall score of 154.8, and a mean Function Level score of 3.4. Table 5.2 outlines the balance ability of subjects in Group 2. Similar to Group 1, these subjects were physically able to complete the tests. However, their balance disorder affected them to a much larger degree.

SUBJECT	AGE	SOT OVERALL SCORE	MCT OVERALL SCORE	FUNCTION LEVEL SCORE
5	61	49	161	2
7	41	N/A	N/A	5
9	56	55	145	2
10	56	52	178	5
12	57	48	135	3
MEAN	54.2	51	154.8	3.4
ST DEV	7.7	3.2	18.8	1.5

Table 5.2: **Group 2 Balance Control Ability**

5.1.3 Subjective Data: Post Testing

Overall, subjects in Group 1 did not believe that they benefited from the prosthesis to a great degree. On a scale between 1 and 10, Group 1 scored the usefulness of the prosthesis at 3.7 ±3.1. When given the opportunity to comment on the prosthesis, some subjects in Group 1 found the tactors to be more of a distraction than a balance aid. The majority of the subjects did state, however, that they could see how the prosthesis could have been useful when their balance control was worse, i.e. during their postoperative period.

Subjects in Group 2 found the prosthesis to be very helpful, indeed. As a group, they scored the usefulness of the prosthesis at 9.2 ±1.3. In general, they were very impressed with the extent to which the prosthesis helped them. In fact, during testing, one patient expressed her unwillingness to complete test runs without the prosthesis for fear of falling. Furthermore, some subjects noted how useful the training session was in helping them learn to understand the tactile information.

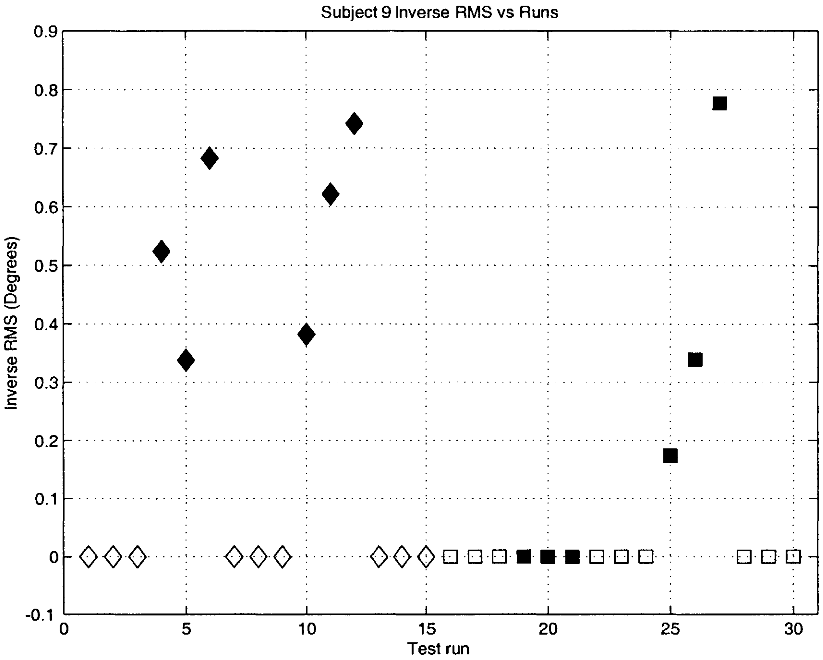

Figure 5-1: **Subject 9 SOT Test Summary (1/ (RMS Θ).** Diamond markers are SOT 5 tests and square markers ore SOT 6 tests. If the marker is filled, the test was run with tactors and if it is not filled, it was run with out tactors.

5.1.4 Objective Data

SOT Results

SOT's measure the prosthesis' ability to increase balance control during quiet stance. Figure 5-1 shows Sets 1 and 2 SOT scores for subject 9. Because we are taking the reciprocal of RMS Θ, better balance control is indicated my higher score, or higher markers in Figure 5-1 (See Appendix B for data tables and Appendix C for individual subject performance plots).

A hypothesis test was used to determine the statistical significance of the SOT results. The null hypothesis states that the balance prosthesis does not reduce body sway, (increase 1/(RMS Θ). A t value was calculated for each parameter and a one-tailed paired t-test was used to determine if the results were significant with a p value < 0.05. Table 5.3 and Table 5.4 are hypothesis test summaries for Group 1 and

Group 2, respectively, calculated by subject and as an entire group. A 0 accepts the null hypothesis and a 1 is a rejection of the null hypothesis. That is, a 1 represents a significant increase in balance control.

SUBJECT	1/(RMS Θ SOT 5)	1/(RMS Θ SOT 6)
1	1	1
2	0	0
3	1	0
4	0	0
6	0	0
8	1	0
11	0	1
13	0	0
14	1	1
ALL	1	1

Table 5.3: **Group 1 SOT Hypothesis Test Summary** The null hypothesis (indicated by the zero) means that the prosthesis did not reduce the respective parameter to a significant degree (a p value < 0.05). Conversely, the number one indicates that the prosthesis did reduce the respective parameter to a significant degree.

SUBJECT	1/(RMS Θ) SOT 5	1/(RMS Θ SOT 6)
5	0	1
7	1	1
9	1	1
10	1	1
12	1	1
ALL	1	1

Table 5.4: **Group 2 SOT Hypothesis Test Summary**The null hypothesis (indicated by the zero) means that the prosthesis did not reduce the respective parameter to a significant degree (a p value < 0.05). Conversely, the number one indicates that the prosthesis did reduce the respective parameter to a significant degree.

MCT Results

MCT's[1] were incorporated into the testing protocol to determine how well a subject could recover from a horizontal perturbation. Figure 5-2 shows a sample MCT test result taken from subject 3. This curve displays an average Θ curve for all the Back Medium MCT's, six runs for No Tactors (NT) and six runs for With Tactors (WT). Notice the sharp increase in Θ as the body leans at the onset of the translation. The body reaches a maximum tilt and then recovers. Three measurements are taken from MCT signals: recovery time, peak deflection, and RMS Θ. (Appendix D and Appendix E contain MCT result plots for Group 1 and Group 2, respectively. Appendix B contain tabulated MCT results.)

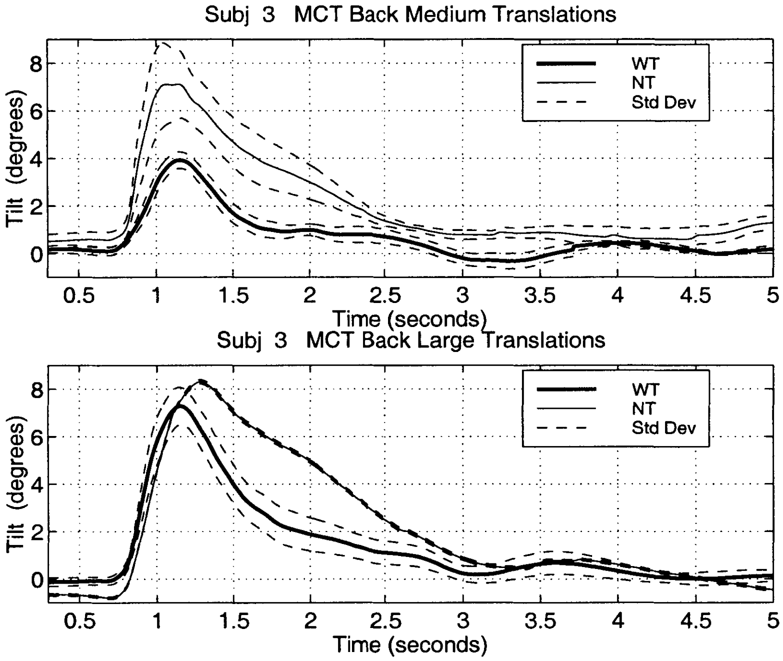

Figure 5-2: **MCT Sample curve.**

A hypothesis test was used to determine the statistical significance of the MCT parameters. The null hypothesis states that the balance prosthesis does not increase

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[1] Because of a software error, subject 1 has no recorded MCT data.

the subject's ability to regain balance, or reduce the specific parameter. A t value for each parameter was calculated and a one-tailed paired t-test was used to determine if the results were significant with a p value < 0.05. Tables 5.5 and 5.6 are hypothesis test summaries for Group 1 and Group 2, respectively, calculated by subject and as an entire group for the results taken from the instrumentation. Tables 5.7 and 5.8 were calculated using the same process for the forceplate data. A zero represents the null hypothesis and a one is a rejection of the hypothesis, or a significant improvement of the respective parameter.

Sub	Recov. Time Med	Recov. Time Large	Peak Def Med	Peak Def Large	RMS Θ Med	RMS Θ Large
1	N/A	N/A	N/A	N/A	N/A	N/A
2	0	0	0	0	0	0
3	0	0	0	0	1	1
4	0	0	0	0	0	0
6	1	1	1	0	0	0
8	0	0	0	0	0	0
11	0	0	0	0	0	0
13	1	0	1	0	0	0
14	0	0	0	0	1	0
ALL	0	1	1	0	1	1

Table 5.5: **Group 1 MCT Θ Hypothesis Test Summary.** The null hypothesis (indicated by the zero) means that the prosthesis did not reduce the respective parameter to a significant degree (a p value < 0.05). Conversely, the number one indicates that the prosthesis did reduce the respective parameter to a significant degree.

Sub	Recov. Time B. Med	Recov. Time B. Large	Peak Def B. Med	Peak Def B. Large	RMS Θ B. Med	RMS Θ B. Large
5	0	1	0	1	0	1
7	0	0	0	0	0	0
9	0	0	1	1	1	1
10	0	0	0	1	0	1
12	0	0	0	1	0	1
ALL	0	1	1	1	1	1

Table 5.6: **Group 2 MCT Θ Hypothesis Test Summary.** The null hypothesis (indicated by the zero) means that the prosthesis did not reduce the respective parameter to a significant degree (a p value < 0.05). Conversely, the number one indicates that the prosthesis did reduce the respective parameter to a significant degree.

Sub	Recov. Time B. Med	Recov. Time B. Large	Peak Def B. Med	Peak Def B. Large	RMS COP B. Med	RMS COP B. Large
1	N/A	N/A	N/A	N/A	N/A	N/A
2	0	0	0	0	0	0
3	1	0	0	0	0	0
4	1	0	0	1	0	1
6	0	0	1	0	0	0
8	0	0	0	0	0	0
11	1	0	0	0	0	0
13	0	0	1	0	0	0
14	0	0	1	0	1	0
ALL	0	1	1	0	0	0

Table 5.7: **Group 1 MCT COP Hypothesis Test Summary.** The null hypothesis (indicated by the zero) means that the prosthesis did not reduce the respective parameter to a significant degree (a p value < 0.05). Conversely, the number one indicates that the prosthesis did reduce the respective parameter to a significant degree.

Sub	Recov. Time B. Med	Recov. Time B. Large	Peak Def B. Med	Peak Def B. Large	RMS COP B. Med	RMS COP B. Large
5	0	0	0	0	0	0
7	0	0	0	0	0	0
9	0	0	0	0	0	0
10	1	0	0	0	0	0
12	0	0	1	0	0	0
ALL	0	0	0	0	0	0

Table 5.8: **Group 2 MCTCOP Hypothesis Test Summary.** The null hypothesis (indicated by the zero) means that the prosthesis did not reduce the respective parameter to a significant degree (a p value < 0.05). Conversely, the number one indicates that the prosthesis did reduce the respective parameter to a significant degree.

5.1.5 Summary

Despite their vestibular disorders, all fourteen subjects were of good health and physically able to accomplish the tests. Unlike Group 1, subjects in Group 2 were severely unable to control their balance when their vision and/or proprioception was compromised.

SOT results are very dramatic. Of 14 subjects, 10 significantly improved their balance in at least one type of SOT. Of the 6 subjects which increased control in both SOT 5 and SOT 6, 4 were from Group 2. Using averages of all WT and NT trials, as shown in Tables A.1 and A.2, the vibrotactile display of estimated body tilt angle reduced sway (as measured by 1/ (RMS Θ)) in 14 out of 14 subjects for SOT 5 and 13 out of 14 subjects for SOT 6.

For Group 1, reductions in sway by individual occurred in 4 out of 9 for SOT 5 and for 3 out of 9 for SOT 6. The actual Group 1 average SOT 5 scores (Table A.1) increased from 0.69 NT to 0.91 WT, a change of 0.22 The average SOT 6 scores increased from 0.58 NT to 0.96 WT, a change of 0.38. For Group 2, significant reductions in sway by individuals occurred in 4 out of 5 for SOT 5 and for 5 out of

5 for SOT 6. The actual Group 2 average SOT 5 scores (Table A.2) increased from 0.30 NT to 0.83 WT, a change of 0.53 The average SOT 6 scores increased from 0.58 NT to 0.72 WT, a change of 0.14. Thus, the largest change over both groups and conditions was for Group 2's SOT 5 score, while the smallest change was for Group 2's SOT 6 score.

The MCT response to perturbations was characterized with six parameters: three each for the large and for the medium perturbations. These six parameters were measured from both the instrumentation signal, Θ, and the forceplate data, COP. Considering group averages, and using instrumentation derived data, 4 out of 6 parameters were significantly reduced, as shown in Tables 5.5 and 5.6 for Group 1 while 5 out of 6 parameters were significantly reduced for Group 2.

5.2 Discussion

5.2.1 SOT Topics

The precursor to a balance prosthesis via vibrotactile display was successful in reducing AP sway in subjects with vestibular disorders. The most dramatic SOT improvements in balance control occurred for subjects in Group 2. Four subjects from Group 2 that volunteered for the experiment came into the Vestibular lab at MEEI with minimal balance control and were practically unable to complete SOT's without the balance prosthesis. With the prosthesis, however, these subjects showed practically normal balance control. Figure 5-1 clearly displays the extent to which subject 9 benefited from the prosthesis. Each test run without tactors resulted in a fall while most test runs with the tactors did not. Other subjects from Group 2 show similar results.

Considering the increases in balance control, Group 1 had fairly good balance to begin with so the increases aren't as dramatic in SOT 5. Because they have compensated for their vestibular disorder, they are not ordinarily very visually dependent. Thus in SOT 6, where they have a visual distortion, the are in a position to rely upon the additional information from the tactors and discard the misleading visual input. This accounts for the relatively large change from the NT to the WT condition in SOT 6 and not in SOT 5.

Group 2 has more severe balance disorders than Group 1. Such people are typically very dependent on visual input. In SOT 5, where there is no visual information, they are able to make use of the vibrotactile information to decrease their RMS Θ. Because there is more room for performance improvement, compared to Group 1, they are able to gain a greater increment of performance. But the story changes for SOT 6 when these visually dependent subjects get a distorted signal that they are normally accustomed to relying upon. They are still depending on visual input even if it is unreliable. Thus, they are not able to take full advantage of the vibrotactile signal since it is in conflict with vision. As a result, they show only a relatively small improvement in performance, as compared to the Group 1 subjects in SOT 6 and the Group 2 subjects in SOT 5. This phenomena can be seen in the beginning of the SOT 6 session in Figure 5-1. Here, subject 9 falls in the first three SOT 6 runs with tactors on. It took this subject a few runs to confide in the tactile information rather than the distorted visual information.

The increase in balance control for SOT's can be explained by one of two reasons. First, the prosthesis provided the subjects with spatial orientation cues that increased their ability to maintain stable posture. Second, the prosthesis was used as an alert, notifying the subject that their body tilt was out of the threshold. In other words, it was not the tilt information that increased balance control, but being forced to concentrate on balance. Determining which reasoning is correct is not a simple task. The standard method would be to interleave tests with two different firing methods, the one with spatial coding and another that would fire all tactors at once whenever the subject tilted outside of the threshold of balance. Because it took some time for subjects to trust the tactile information and begin to use it effectively, such a control experiment is not an optimal solution. Giving them two different methods would only confuse them and destroy this confidence. A better method would be to test the latter method separately.

5.2.2 MCT Topics

The varying success between SOT's and MCT's can be due to the fact that the platform is fixed during MCT's, enabling subjects to use proprioception (the main input for recovery) to regain balance. A better test would be to have the platform sway-referenced at the end of the perturbation, denying them of proprioception and leaving them with minimal balance control without the prosthesis. This test is not a standard option on the Equitest and would involve customized programming.

MCT Θ and COP results are not highly correlated. The instrumentation detected large improvements in balance control from the prosthesis. The COP data, however, did not confirm this. This discrepancy suggests that subjects were bending at the hips, giving rise to changes in Θ and relatively stable COP. This result is logical because subjects were better *informed* to reduce Θ and not COP, because they were given Θ directly. Moreover, the difference in the results can be attributed to different balance strategies. In other words, the prosthesis may have helped subjects invoke the ankle strategy for stabilization, as opposed to the hip strategy. The difference between the two strategies would account for the larger differences in Θ and a stable COP. Determining which strategy was being used is out of the scope of this project. What can be stated, however, is that for at least five subjects, tactile information increased their ability to control their body segments.

Another explanation for the varying success in MCT's could lie in the number of recorded test runs. Biological data is very noisy. As more data is collected and averaged, the true result begins to emerge from the noise. It is possible that the protocol did not include enough MCT runs to produce significant data.

5.2.3 Other Topics

Nashner's model of balance describes the body as an inverted pendulum. From a controls point of view, two signals are needed to stabilize this system, rate and position or rate and acceleration. However, the balance prosthesis only feeds back one signal, Θ, and was successful in significantly stabilizing bodies that were otherwise unstable. One of two conclusions can be made from this result. First, the body during quiet stance cannot be modeled as an inverted pendulum, or second, the CNS is deriving rate information by other means.

This experiment produced positive results with vestibulopathic subjects while the previous attempt did not. I attribute the difference in results to two factors. First, the current configuration provided an accurate tilt estimate while the previous experiment might not have. Secondly, the current training method exploited a technique that is specifically designed for balance rehabilitation. This training method was used to allow subjects to develop confidence in the prosthesis.

Some subjects in Group 1 stated that the prosthesis was more of a distraction than an aid. These subjects did not find the tactors very useful because they have compensated for their unilateral loss of vestibular function to such an extent, that they did not *need* the prosthesis. This correlates well with the recorded data; their body sway was rarely out of the stable threshold and the tactors rarely fired.

Allowing subjects from Group 1 to be tested before subjects in Group 2 was very valuable. These subjects have better balance control and were able to complete the testing protocol with small amounts of difficulty. These tests provided valuable experience on how to handle subjects with vestibular disorders. In addition, the standard test protocol described in Table 4.1 wasn't defined until the third subject and was further modified to make statistical calculation easier. Subjects from Group 1 created the opportunity to adjust the protocol and learn how to correctly administer the experiment.

Some subjects were unable to run the same number of tests as other subjects because of fatigued leg muscles. For this reason, there was at least one rest period during each experiment. Even so, fatigue could have led to increased body sway.

5.2.4 Recommendations

To improve efficiency of testing and the validity of the results, I would design the test protocol around the statistical analysis. That is, I would take an equal number of tests under the two conditions, NT and WT. In addition, I would standardize the number of tests and eliminate the last two sets of test runs in Table 4.1.

In the previous experiment, touch contact significantly reduced body tilt when compared to the balance prosthesis. One reason that was discussed was processing speed. That is, the CNS reacts faster to fingertip stimulation than to tactor stimulation. The training session may have addressed this issue. By familiarizing the subjects to tactor information before testing, the subjects were given time to understand how to react. It would be interesting to see how the new test protocol compares to light fingertip touch, which could be included into the protocol. Furthermore, other information, such as rate ($\dot{\Theta}$), could be given to investigate the optimal signal for balance control.

There are many ways to convey AP tilt information via vibrotactile display. Another method creates a virtual wall in front and in back of the subject. A tactor is fired whenever the body axis intersects with the virtual wall. The importance behind conveying the information in an effective manner concerns the subjects themselves. People with vestibular disorders have very little confidence in their ability to maintain posture, especially when vision is impaired. Thus, the transmission method is very important.

To be truly useful, the final prosthesis must accommodate all types of movement and in every direction so that it may be used during daily activities. The first step would be to expand the prosthesis to detect ML tilt as well as AP tilt. Afterwards, the prosthesis must be expanded to accommodate movement such as walking. I suggest a new type of prosthesis that uses joint angles in addition to rate and acceleration to calculate the position and trajectory of the body's COM in three-dimensional space. This information could be fed back to the subject via vibrotactile display.

Chapter 6

Conclusion

This project further developed the hardware and software involved in a precursor to a balance prosthesis via vibrotactile display. The use of the prosthesis, which provides knowledge of AP body tilt with respect to vertical, made a dramatic increase in balance control during quiet stance. This, however, has only limited applications to activities of daily living (ADL). There was a significant improvement of balance in response to applied disturbances. Although less dramatic, this result may be more applicable to ADL. In addition, this study proved that tilt information alone is sufficient to increase balance under both conditions, thus contradicting the inverted pendulum model of postural control.

Appendix A

SOT Numeric Results

SUB	SOT 5 NT	SOT 5 WT	SOT 6 NT	SOT 6 WT
1	0.88 ±0.05	1.50 ±0.17	0.99 ±0.19	2.56 ±0.61
2	0.79 ±0.11	0.95 ±0.04	0.72 ±0.06	0.97 ±0.24
3	0.70 ±0.09	1.02 ±0.11	0.65 ±0.08	1.02 ±0.20
4	0.41 ±0.05	0.46 ±0.11	0.27 ±0.06	0.38 ±0.07
6	0.72 ±0.12	0.73 ±0.19	0.62 ±0.17	0.72 ±0.14
8	0.64 ±0.08	0.84 ±0.07	0.29 ±0.03	0.37 ±0.09
11	0.96 ±0.12	0.99 ±0.17	0.86 ±0.04	1.35 ±0.15
13	0.28 ±0.07	0.35 ±0.09	0.25 ±0.09	0.23 ±0.07
14	0.79 ±0.15	1.33 ±0.12	0.60 ±0.06	1.01 ±0.12
ALL	0.69 ±0.09	0.91 ±0.12	0.58 ±0.09	0.96 ±0.19

Table A.1: **Group 1 SOT Results Summary: 1/(RMS Θ) (1/degrees)** Entries are mean ± standard error for all available runs. NT is No Tactors are activated. WT is With Tactors activated.

Sub	SOT 5 NT	SOT 5 WT	SOT 6 NT	SOT 6 WT
5	0.43 ±0.08	0.64 ±0.12	0.47 ±0.06	0.83 ±0.09
7	0.68 ±0.09	1.43 ±0.05	0.87 ±0.10	1.17 ±0.14
9	0.00 ±0.00	0.55 ±0.07	0.00 ±0.00	0.21 ±0.13
10	0.09 ±0.05	0.81 ±0.13	0.07 ±0.04	0.85 ±0.16
12	0.27 ±0.12	0.73 ±0.03	0.01 ±0.01	0.56 ±0.10
All	0.30 ±0.07	0.83 ±0.08	0.58 ±0.04	0.72 ±0.12

Table A.2: **Group 2 SOT Results Summary: 1/(RMS Θ) (1/degrees)** Data entries are mean ± standard error for all available runs. NT is No Tactors are activated. WT is With Tactors activated.

Appendix B

MCT Numeric Results

Sub	Recovery Time Medium NT	Recovery Time Medium WT	Recovery Time Large NT	Recovery Time Large WT
2	1.83 ±0.69	1.11 ±0.94	1.76 ±0.68	1.32 ±0.47
3	1.43 ±0.20	0.98 ±0.22	2.19 ±0.38	0.38 ±0.23
4	2.65 ±0.23	2.58 ±0.27	2.49 ±0.25	2.44 ±0.35
6	1.59 ±0.47	0.58 ±0.49	1.10 ±0.48	0.17 ±0.05
8	0.74 ±0.46	1.29 ±0.55	0.80 ±0.32	2.01 ±0.46
11	0.30 ±0.17	0.08 ±0.04	0.60 ±0.49	0.71 ±0.22
13	0.42 ±0.15	0.25 ±0.08	0.78 ±0.45	0.98 ±0.17
14	0.84 ±0.43	0.19 ±0.05	1.51 ±0.67	1.60 ±0.62

Table B.1: **Group 1 MCT Θ Recovery Time (seconds)**

Sub	Recovery Time Medium NT	Recovery Time Medium WT	Recovery Time Large NT	Recovery Time Large WT
5	0.10 ±0.04	0.15 ±0.07	0.91 ±0.34	0.01 ±0.00
7	0.18 ±0.09	0.33 ±0.02	2.14 ±0.29	1.32 ±0.21
9	1.40 ±0.37	1.57 ±0.54	1.88 ±0.44	1.77 ±0.46
10	2.24 ±0.32	2.14 ±0.54	2.11 ±0.36	1.50 ±0.51
12	2.00 ±0.47	2.14 ±0.43	2.69 ±0.21	2.32 ±0.31

Table B.2: **Group 2 MCT Θ Recovery Time (seconds)**

Sub	Recovery Time Medium NT	Recovery Time Medium WT	Recovery Time Large NT	Recovery Time Large WT
2	0.42 ±0.14	0.23 ±0.01	0.37 ±0.02	0.28 ±0.02
3	1.42 ±0.52	0.41 ±0.07	1.27 ±0.45	0.38 ±0.05
4	0.32 ±0.05	0.19 ±0.03	0.29 ±0.02	0.30 ±0.01
6	0.21 ±0.01	0.20 ±0.01	0.33 ±0.01	0.32 ±0.01
8	0.19 ±0.03	0.19 ±0.01	0.30 ±0.02	0.31 ±0.01
11	1.63 ±0.61	0.30 ±0.04	0.73 ±0.45	0.32 ±0.02
13	0.43 ±0.20	0.25 ±0.01	0.39 ±0.06	0.58 ±0.24
14	2.28 ±0.36	3.00 ±0.00	3.00 ±0.00	2.31 ±0.44

Table B.3: **Group 1 MCT COP Recovery Time Results (seconds)**

Sub	Recovery Time Medium NT	Recovery Time Medium WT	Recovery Time Large NT	Recovery Time Large WT
5	0.17 ±0.01	0.16 ±0.01	0.27 ±0.03	0.24 ±0.05
7	0.91 ±0.28	0.43 ±0.07	2.14 ±0.36	2.00 ±0.48
9	0.26 ±0.07	0.29 ±0.08	0.72 ±0.32	0.33 ±0.08
10	3.00 ±0.00	2.16 ±0.53	2.89 ±0.11	2.57 ±0.43
12	0.54 ±0.10	1.51 ±0.56	1.01 ±0.38	0.97 ±0.38

Table B.4: **Group 2 MCT COP Recovery Time Results (seconds)**

Sub	Peak Def Medium NT	Peak Def Medium WT	Peak Def Large NT	Peak Def Large WT
2	3.06 ±0.31	2.64 ±0.36	4.42 ±0.29	4.73 ±0.56
3	7.54 ±1.82	3.97 ±0.38	8.34 ±0.87	7.37 ±0.85
4	6.20 ±0.57	5.49 ±0.61	7.27 ±0.74	6.73 ±0.64
6	2.97 ±0.67	1.63 ±0.74	2.37 ±1.73	1.76 ±0.38
8	2.79 ±0.73	3.74 ±0.69	4.27 ±0.58	5.84 ±0.48
11	1.36 ±0.60	1.12 ±0.14	-0.14 ±0.53	2.21 ±0.31
13	2.83 ±0.45	1.88 ±0.23	4.51 ±0.85	4.11 ±0.43
14	1.24 ±0.64	1.22 ±0.34	2.27 ±0.76	2.81 ±0.44

Table B.5: **Group 1 MCT Θ Peak Deflection Results (degrees)**

Sub	Peak Def Medium NT	Peak Def Medium WT	Peak Def Large NT	Peak Def Large WT
5	1.56 ±0.44	1.45 ±0.49	3.68 ±0.58	0.66 ±0.03
7	1.34 ±0.38	2.39 ±0.24	3.07 ±0.29	4.78 ±1.03
9	15.19 ±1.53	5.53 ±1.47	20.91 ±2.26	9.52 ±1.92
10	6.28 ±0.67	7.06 ±1.23	12.33 ±0.83	8.78 ±1.02
12	4.86 ±0.47	4.27 ±0.49	6.48 ±0.37	5.26 ±0.42

Table B.6: **Group 2 MCT Θ Peak Deflection Results (degrees)**

Sub	Peak Def Medium NT	Peak Def Medium WT	Peak Def Large NT	Peak Def Large WT
2	4.29 ±0.06	4.74 ±0.12	5.22 ±0.08	5.41 ±0.07
3	3.77 ±0.20	3.69 ±0.36	3.57 ±0.23	4.61 ±0.21
4	2.20 ±0.12	1.82 ±0.20	3.07 ±0.12	2.34 ±0.12
6	4.51 ±0.26	4.08 ±0.27	5.17 ±0.08	5.54 ±0.09
8	2.86 ±0.19	3.54 ±0.23	3.57 ±0.13	3.85 ±0.15
11	3.81 ±0.28	4.13 ±0.05	4.05 ±0.52	4.57 ±0.23
13	3.59 ±0.25	3.06 ±0.13	4.17 ±0.29	3.90 ±0.11
14	10.97 ±1.41	8.05 ±0.92	12.46 ±1.60	17.05 ±2.48

Table B.7: **Group 1 MCT COP Peak Deflection Results (inches)**

Sub	Peak Def Medium NT	Peak Def Medium WT	Peak Def Large NT	Peak Def Large WT
5	2.82 ±0.13	2.59 ±0.06	3.28 ±0.05	3.27 ±0.06
7	2.20 ±0.09	2.41 ±0.26	3.21 ±0.24	3.84 ±0.17
9	3.46 ±0.74	2.67 ±0.34	11.09 ±7.24	3.12 ±0.46
10	5.66 ±0.15	6.16 ±0.22	6.29 ±0.19	6.79 ±0.19
12	4.57 ±0.11	4.20 ±0.16	4.91 ±0.13	4.75 ±0.11

Table B.8: **Group 2 MCT COP Peak Deflection Results (inches)**

Sub	RMS Θ Medium NT	RMS Θ Medium WT	RMS Θ Large NT	RMS Θ Large WT
2	0.68 ±0.06	1.13 ±0.23	1.27 ±0.12	1.27 ±0.16
3	2.27 ±0.55	1.18 ±0.15	3.19 ±0.23	2.36 ±0.29
4	0.98 ±0.12	0.77 ±0.07	1.35 ±0.08	1.24 ±0.08
6	0.85 ±0.17	0.68 ±0.08	0.84 ±0.08	0.86 ±0.04
8	1.31 ±0.23	1.19 ±0.13	1.98 ±0.21	1.68 ±0.12
11	0.70 ±0.14	0.45 ±0.03	0.57 ±0.12	0.78 ±0.09
13	0.86 ±0.11	0.78 ±0.06	1.40 ±0.19	1.43 ±0.15
14	0.62 ±0.06	0.47 ±0.05	1.00 ±0.27	0.72 ±0.11

Table B.9: **Group 1 MCT RMS Θ Results (degrees)**

Sub	RMS Θ Medium NT	RMS Θ Medium WT	RMS Θ Large NT	RMS Θ Large WT
5	0.94 ±0.10	0.79 ±0.10	1.16 ±0.05	1.05 ±0.07
7	0.89 ±0.14	0.84 ±0.04	1.21 ±0.12	1.33 ±0.29
9	5.06 ±0.57	2.27 ±0.49	6.80 ±0.69	2.66 ±0.47
10	2.36 ±0.18	2.30 ±0.48	4.37 ±0.30	2.70 ±0.15
12	1.45 ±0.18	1.18 ±0.13	1.57 ±0.13	1.31 ±0.10

Table B.10: **Group 2 MCT RMS Θ Results (degrees)**

Sub	RMS COP Medium NT	RMS COP Medium WT	RMS COP Large NT	RMS COP Large WT
2	0.76 ±0.04	1.01 ±0.16	1.38 ±0.10	1.42 ±0.07
3	0.75 ±0.08	0.75 ±0.12	0.74 ±0.06	1.08 ±0.07
4	0.59 ±0.09	0.59 ±0.09	0.80 ±0.05	0.68 ±0.04
6	1.41 ±0.17	1.22 ±0.07	1.35 ±0.09	1.37 ±0.07
8	0.79 ±0.04	1.05 ±0.08	1.07 ±0.06	1.18 ±0.07
11	0.70 ±0.09	0.80 ±0.04	0.88 ±0.15	1.15 ±0.09
13	0.83 ±0.13	0.68 ±0.06	1.11 ±0.13	0.88 ±0.04
14	2.27 ±0.27	1.63 ±0.13	2.79 ±0.53	3.90 ±0.67

Table B.11: **Group 1 MCT RMS COP Results (inches)**

Sub	RMS COP Medium NT	RMS COP Medium WT	RMS COP Large NT	RMS COP Large WT
5	0.69 ±0.06	0.83 ±0.08	0.76 ±0.03	0.87 ±0.01
7	0.58 ±0.09	0.55 ±0.05	0.81 ±0.10	0.77 ±0.03
9	1.42 ±0.19	1.13 ±0.09	2.55 ±1.08	1.23 ±0.18
10	0.76 ±0.05	1.15 ±0.19	1.13 ±0.08	1.28 ±0.13
12	0.90 ±0.07	0.89 ±0.16	1.14 ±0.09	1.25 ±0.09

Table B.12: **Group 2 MCT RMS COP Results (inches)**

Appendix C

SOT Results

Note: The second (bottom) graph for each subject is a difference plot. It is calculated by subtracting the No tactor parameter result by the With Tactor result. The error bars represent the standard error of each measurement.

X Axis Label	Definition
NT_SOT5	SOT 5 with No Tactors
WT_SOT5	SOT 5 With Tactors
NT_SOT6	SOT 6 with No Tactors
WT_SOT6	SOT 6 With Tactors

Table C.1: **Data Plot Key**

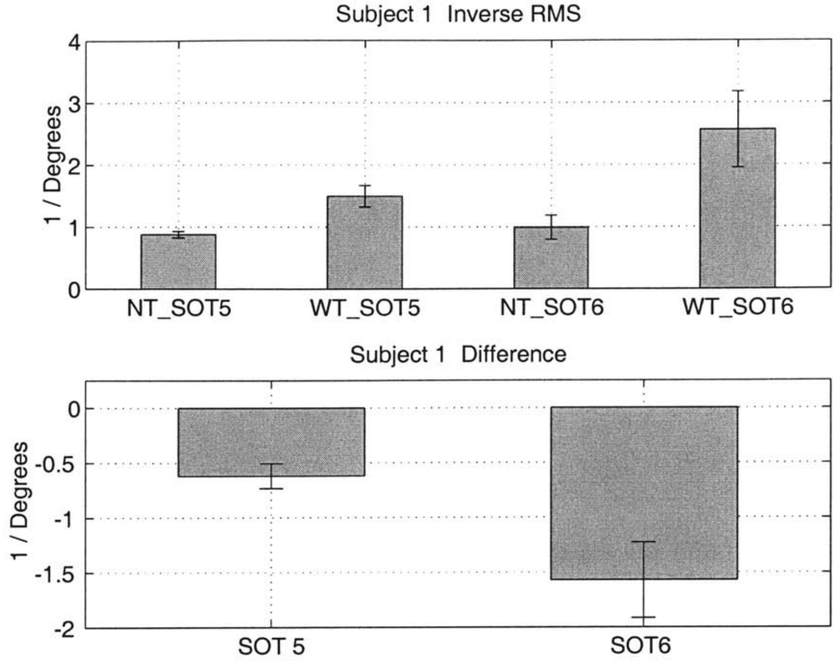


Figure C-1: **Subject 1 SOT Results.**

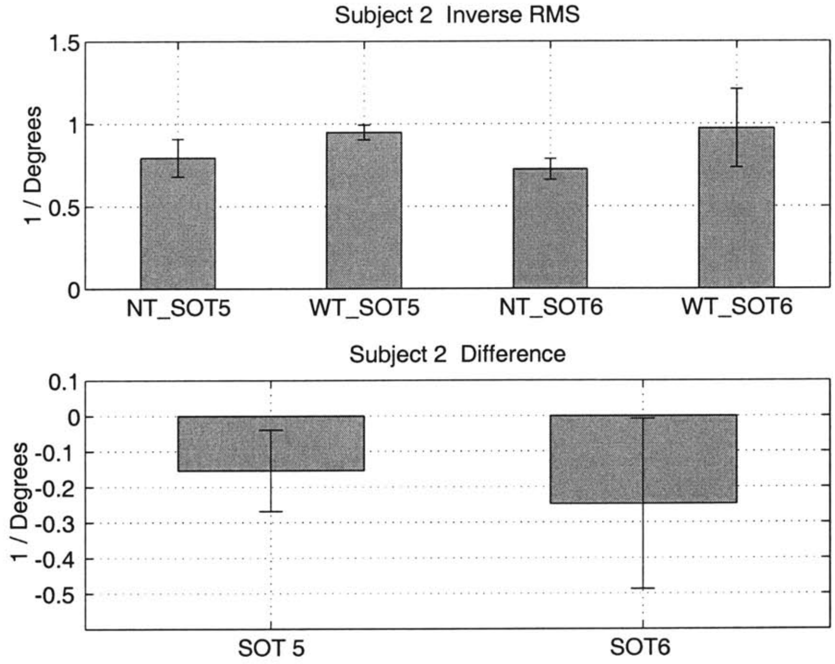


Figure C-2: **Subject 2 SOT Results.**

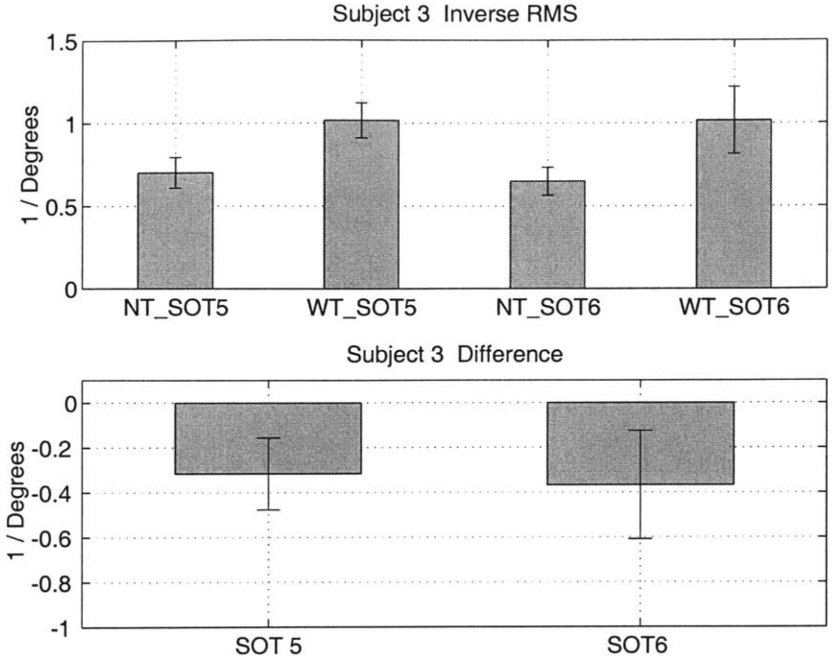


Figure C-3: **Subject 3 SOT Results.**

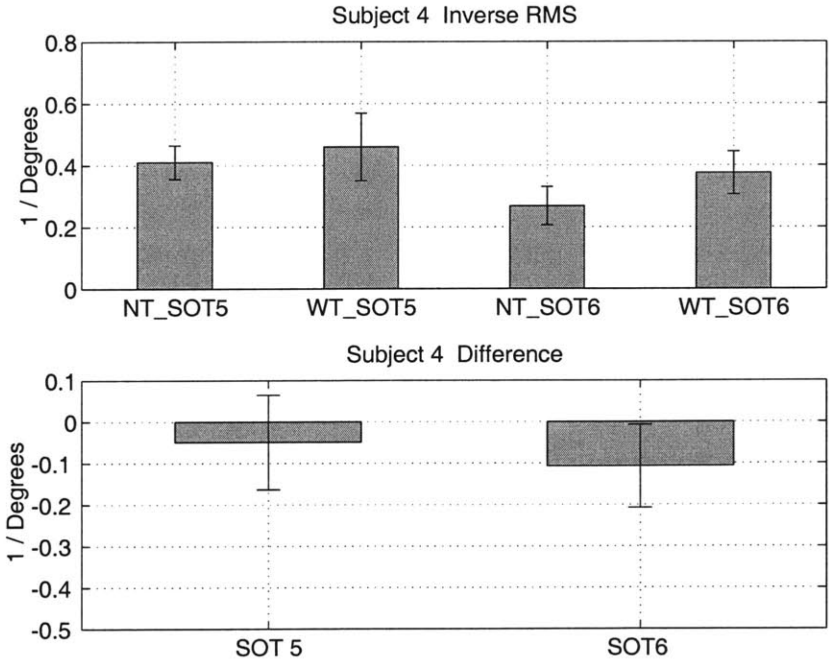


Figure C-4: **Subject 4 SOT Results.**

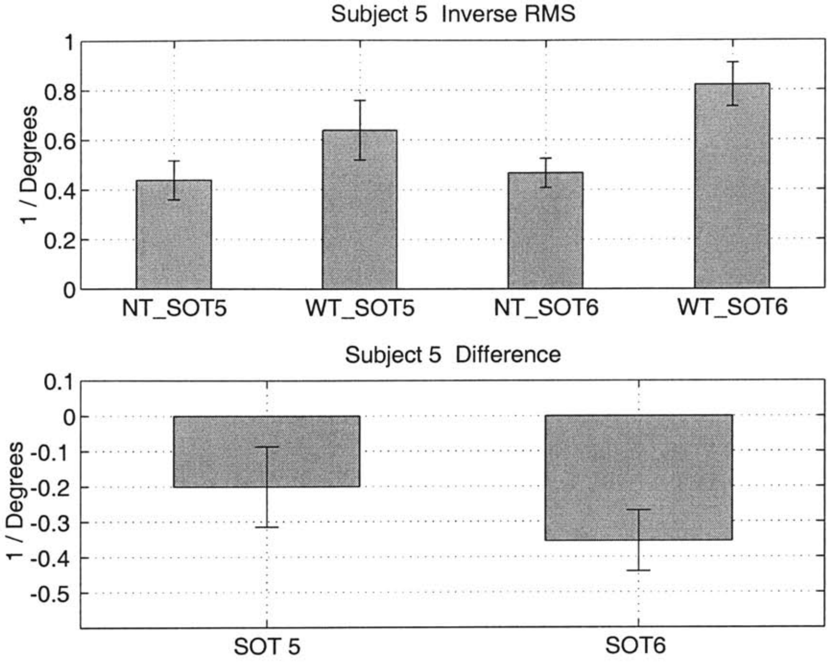


Figure C-5: **Subject 5 SOT Results.**

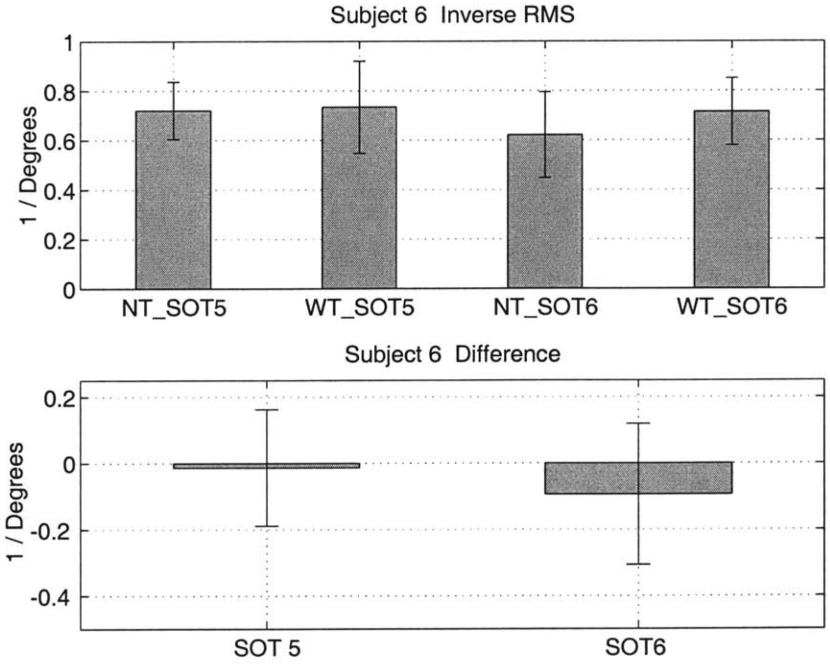


Figure C-6: **Subject 6 SOT Results.**

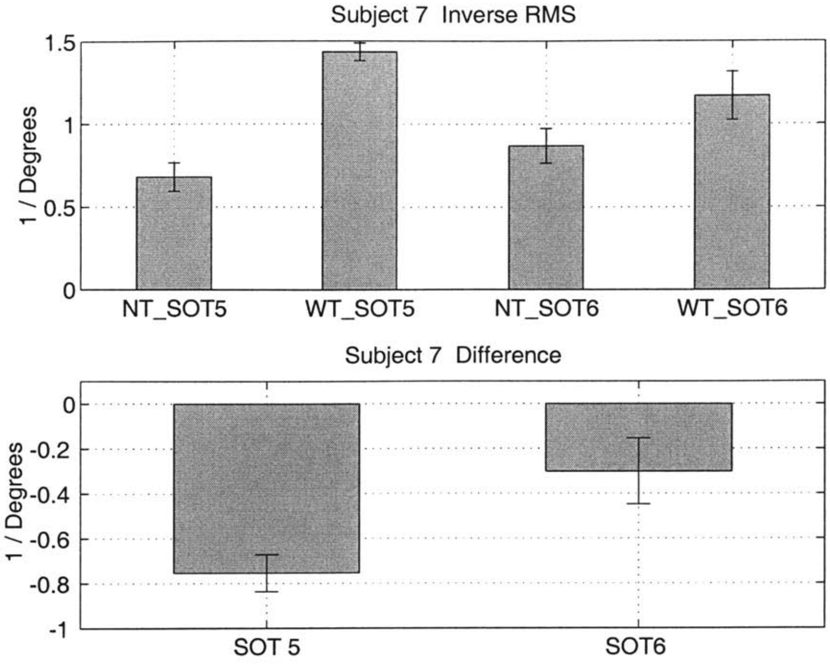


Figure C-7: **Subject 7 SOT Results.**

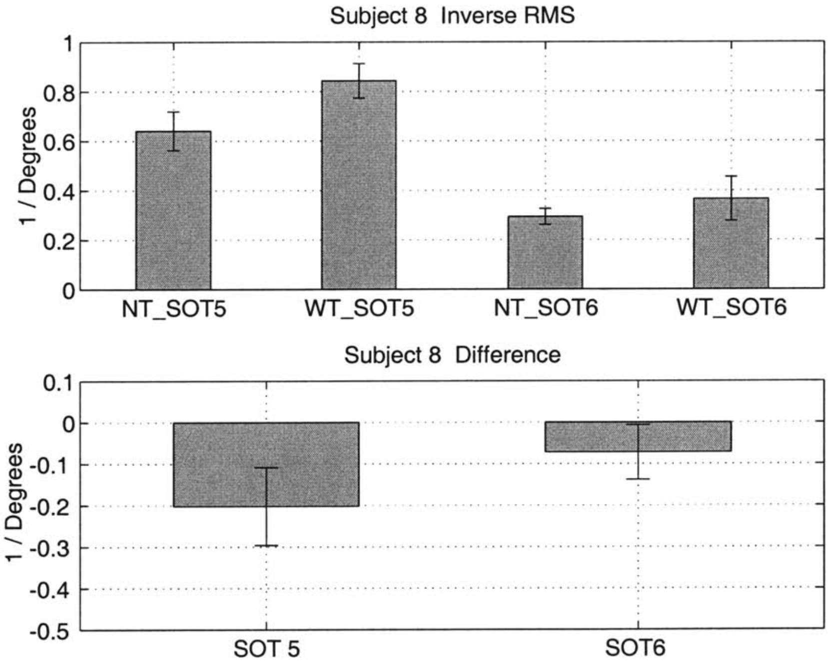


Figure C-8: **Subject 8 SOT Results.**

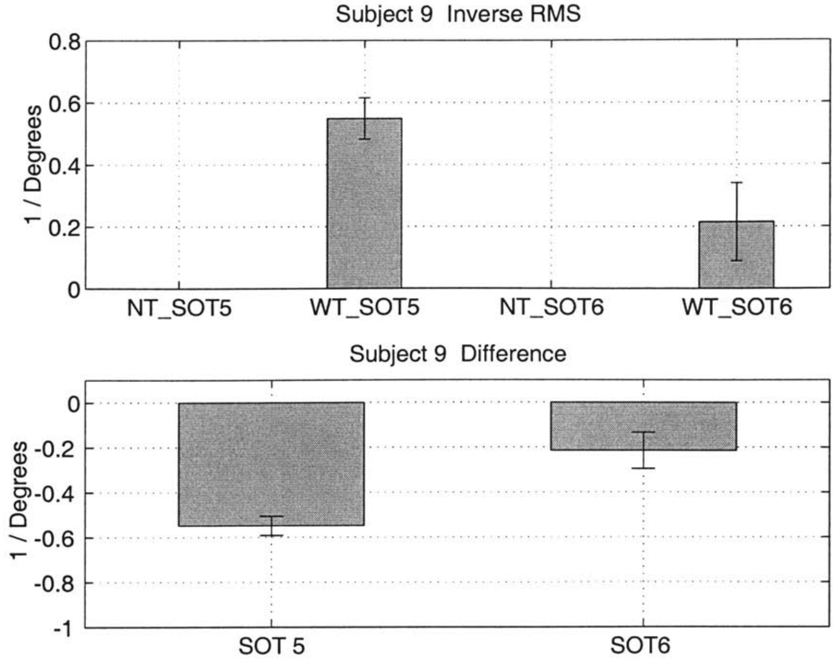


Figure C-9: **Subject 9 SOT Results.**

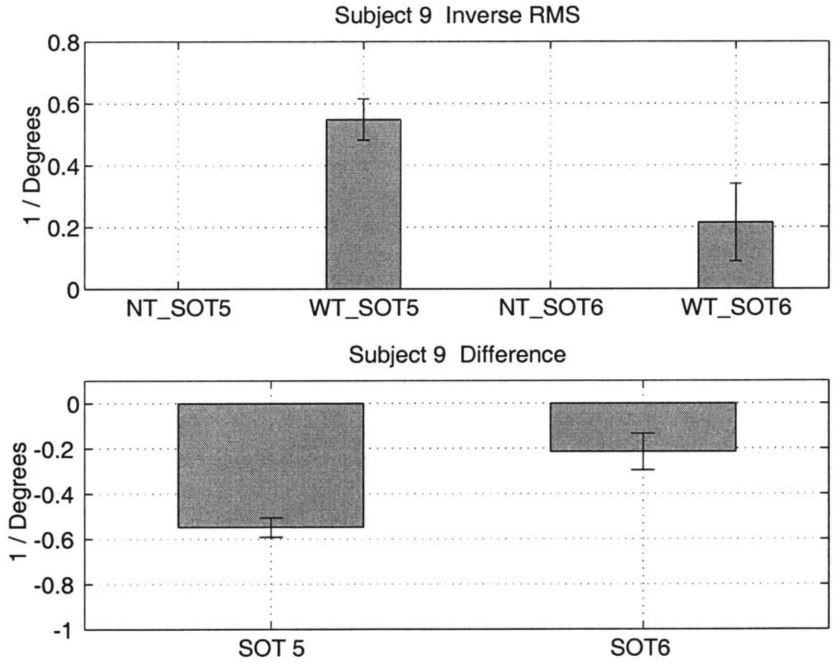


Figure C-10: **Subject 10 SOT Results.**

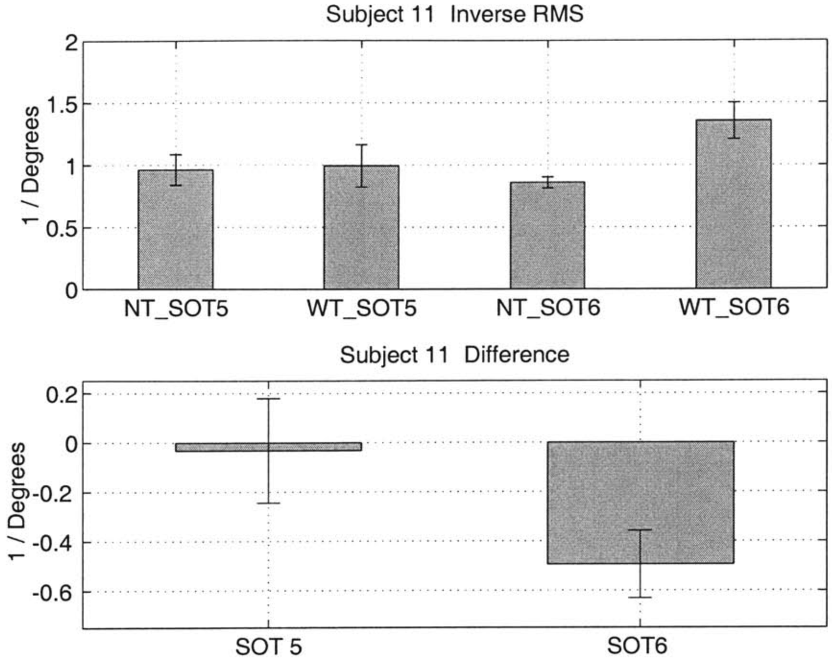


Figure C-11: **Subject 11 SOT Results.**

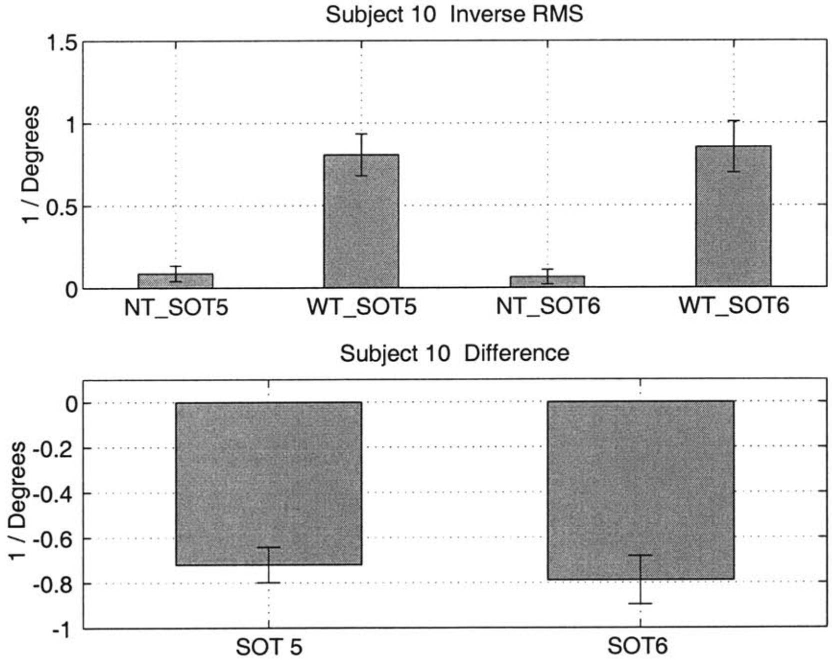


Figure C-12: **Subject 12 SOT Results.**

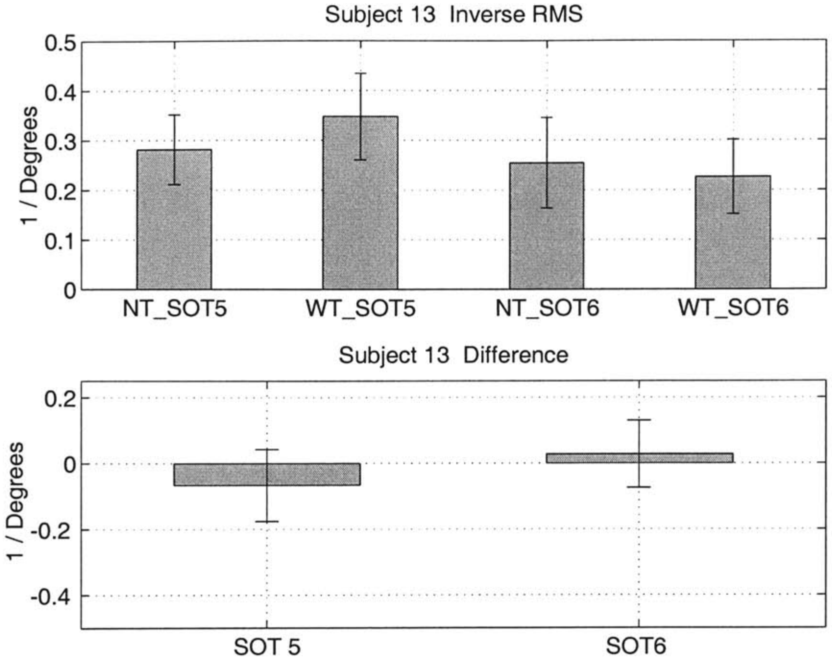


Figure C-13: **Subject 13 SOT Results.**

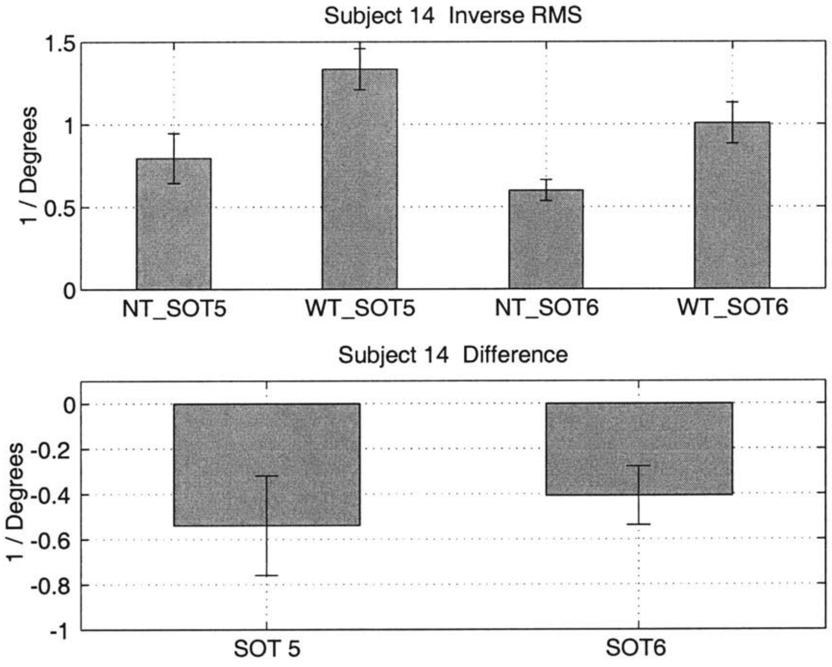


Figure C-14: **Subject 14 SOT Results.**

Appendix D

MCT Θ Results

Note:

The error bars represent the standard error of each measurement.

X AXIS LABEL	DEFINITION
NT_BM	MCT BACK MEDIUM WITH NO TACTORS
WT_BM	MCT BACK MEDIUM WITH TACTORS
NT_BL	MCT BACK LARGE WITH NO TACTORS
WT_BL	MCT BACK LARGE WITH TACTORS

Table D.1: **Data Plot Key**

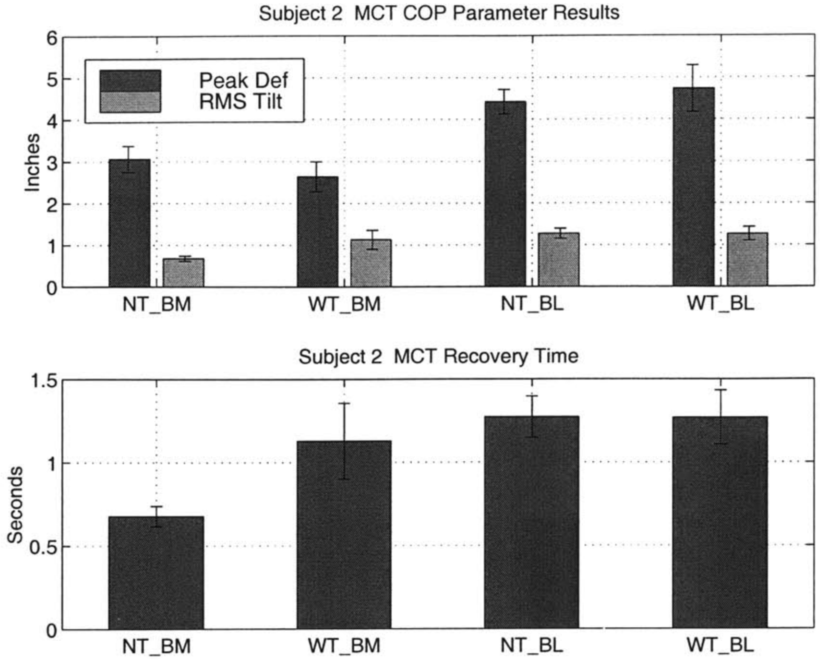


Figure D-1: **Subject 2 MCT Results.**

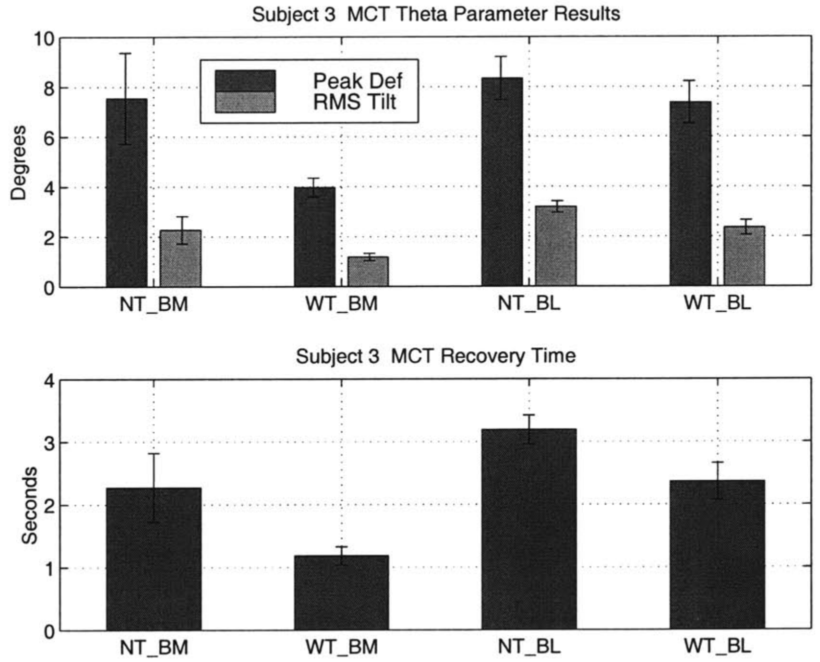


Figure D-2: **Subject 3 MCT Results.**

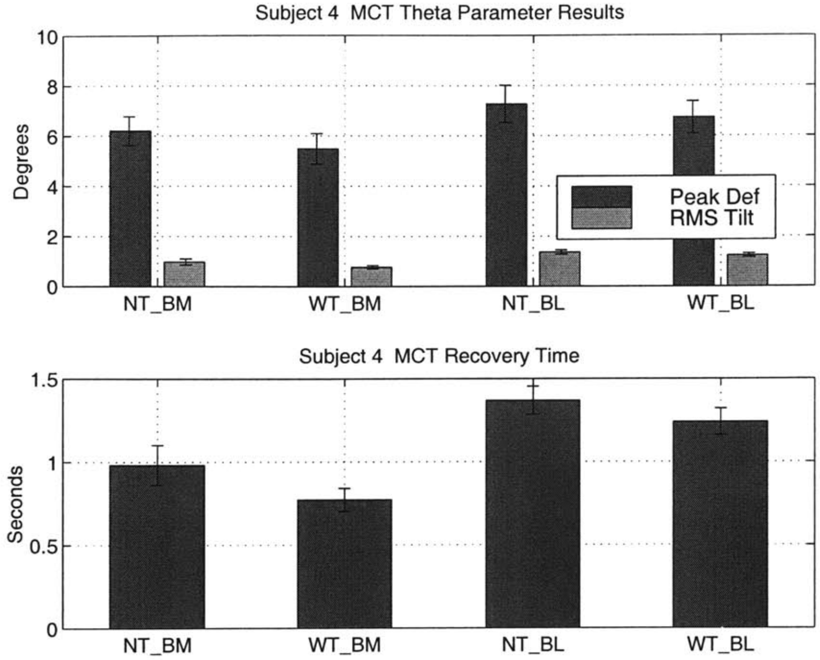


Figure D-3: **Subject 4 MCT Results.**

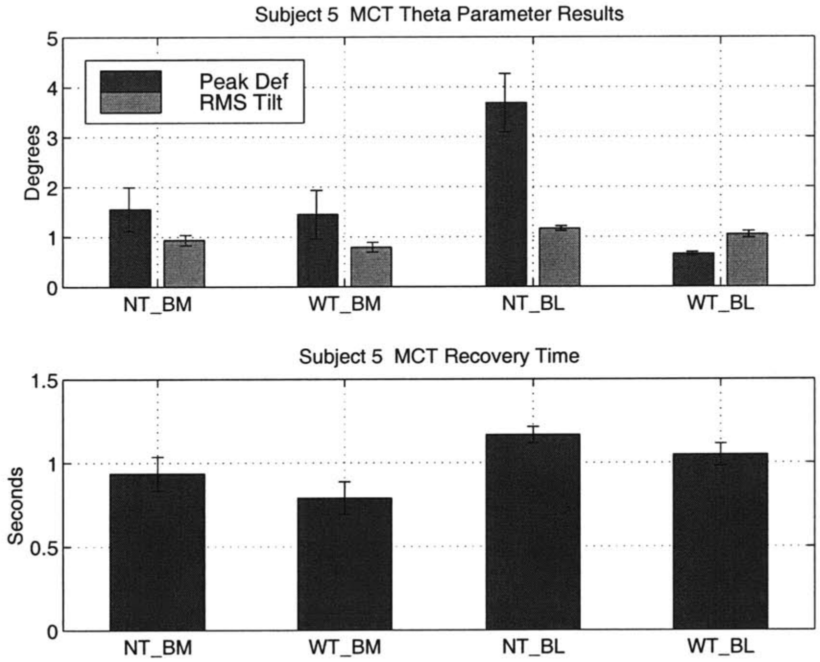


Figure D-4: **Subject 5 MCT Results.**

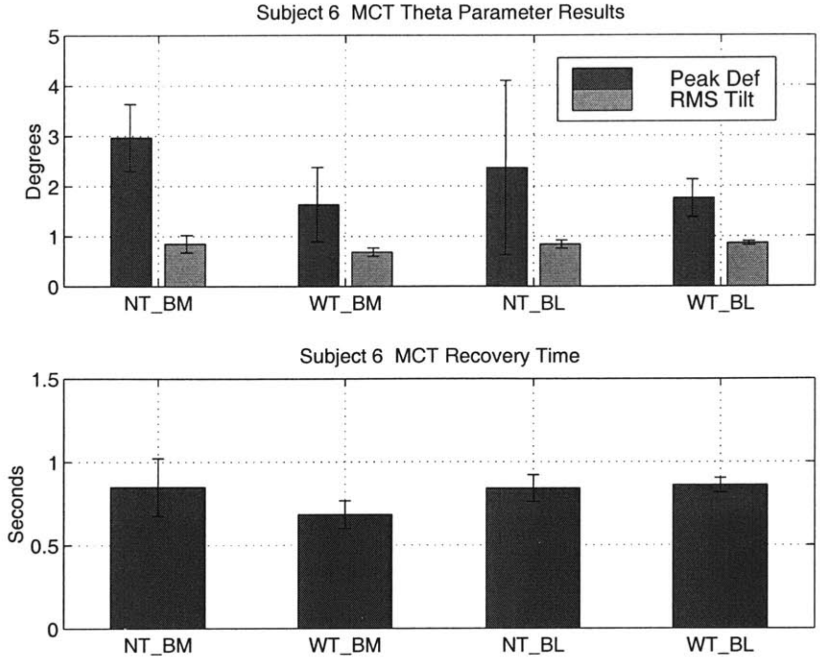


Figure D-5: **Subject 6 MCT Results.**

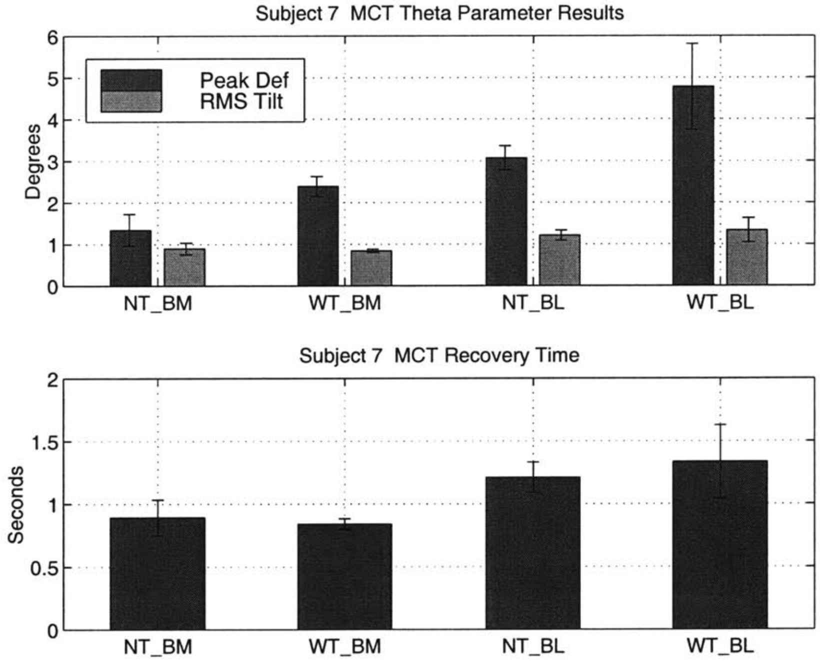
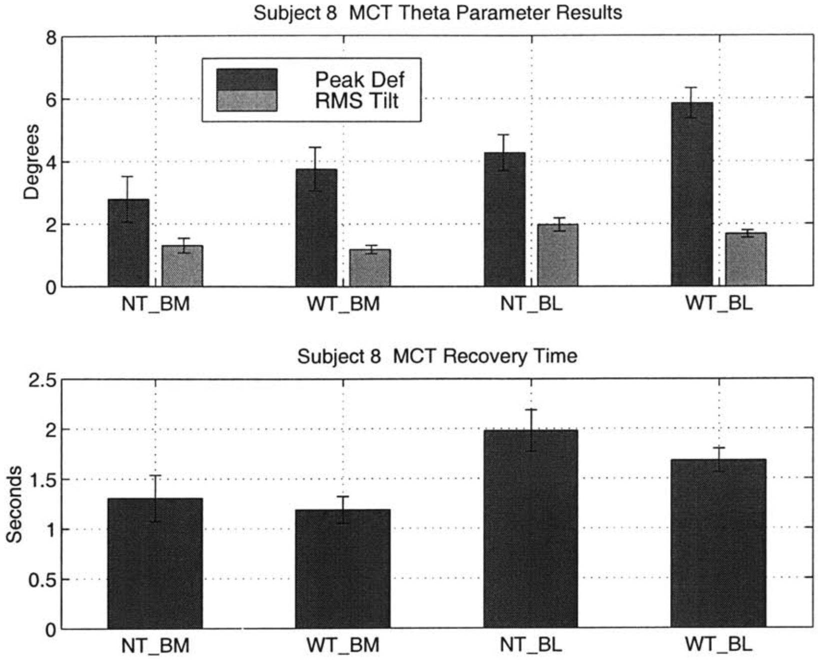
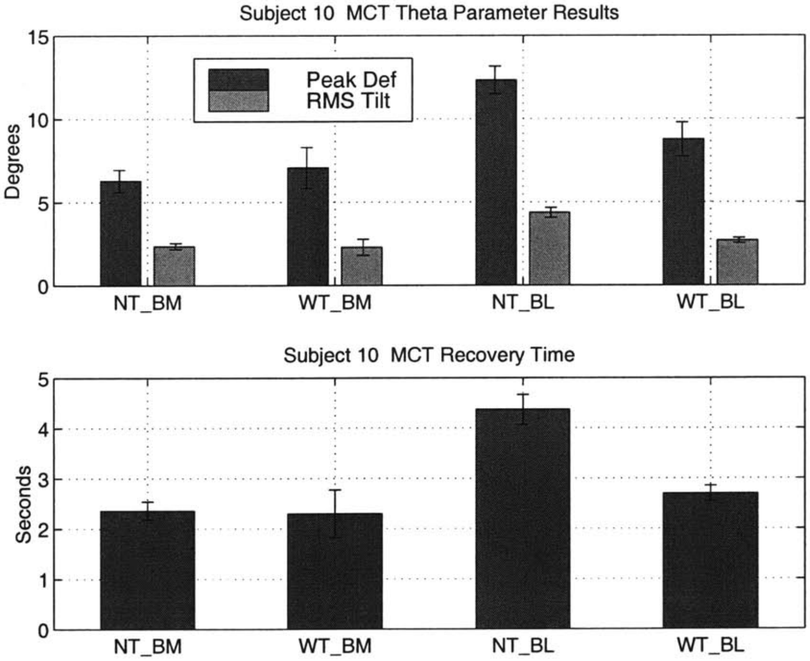


Figure D-6: **Subject 7 MCT Results.**


Subject 8 MCT Theta Parameter Results

Subject 8 MCT Recovery Time

Figure D-7: **Subject 8 MCT Results.**


Subject 10 MCT Theta Parameter Results

Subject 10 MCT Recovery Time

Figure D-8: **Subject 9 MCT Results.**

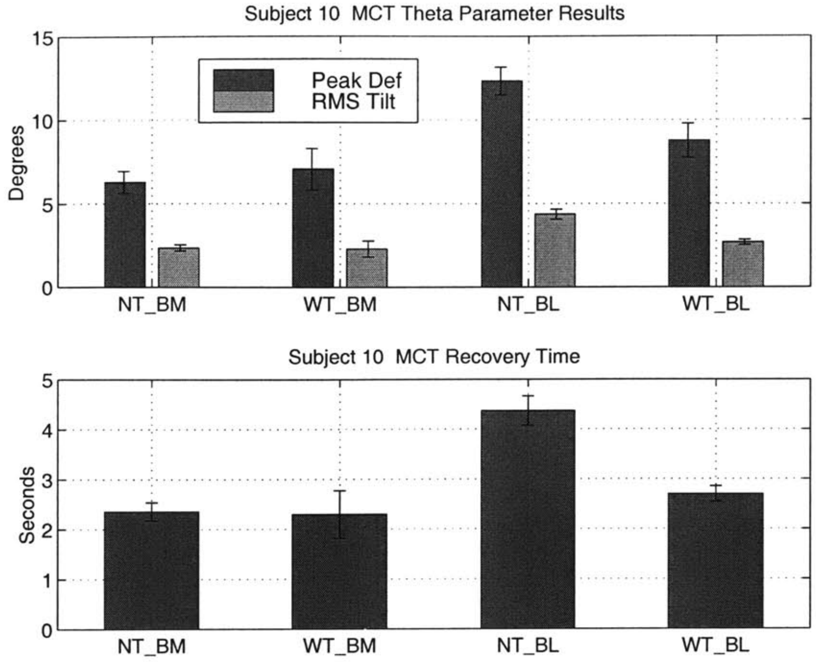


Figure D-9: **Subject 10 MCT Results.**

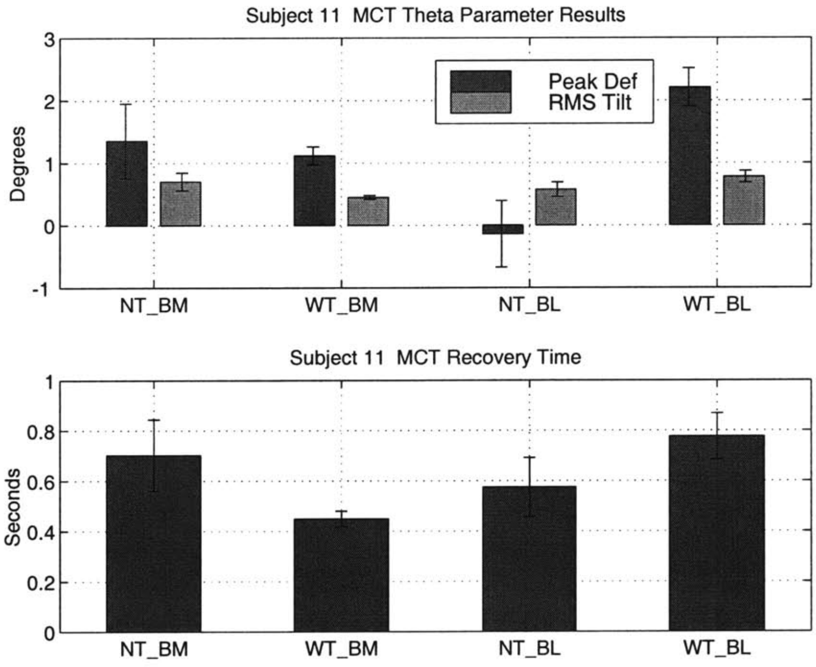


Figure D-10: **Subject 11 MCT Results.**

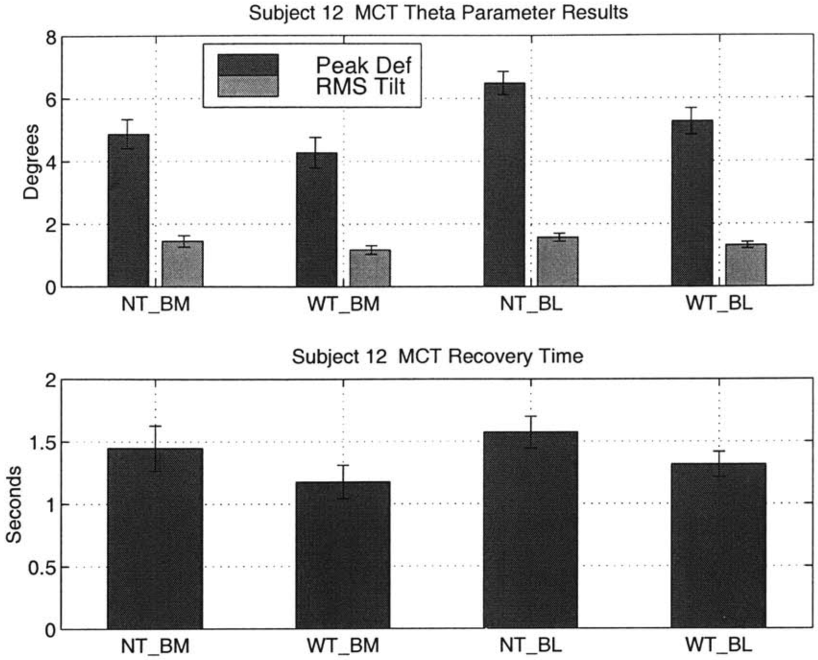


Figure D-11: **Subject 12 MCT Results.**

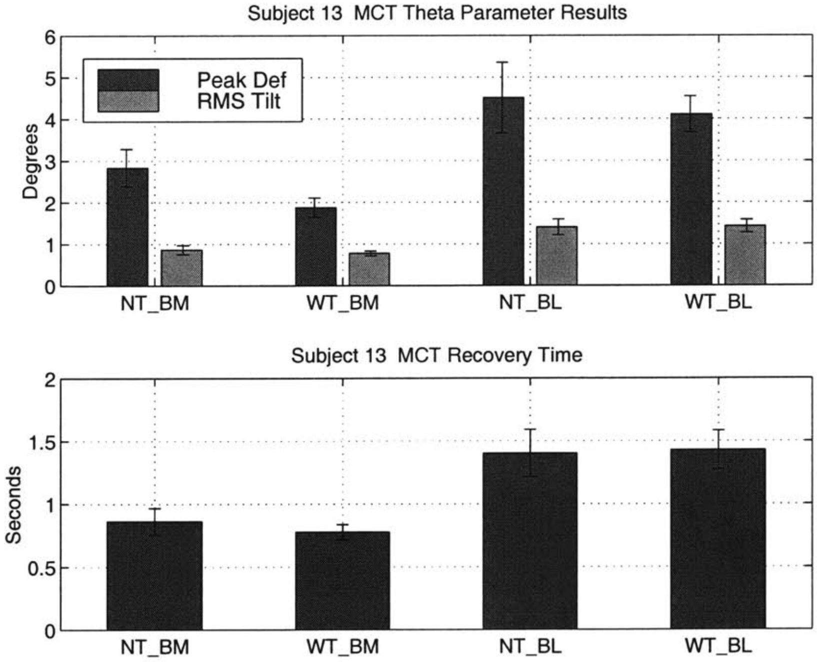


Figure D-12: **Subject 13 MCT Results.**

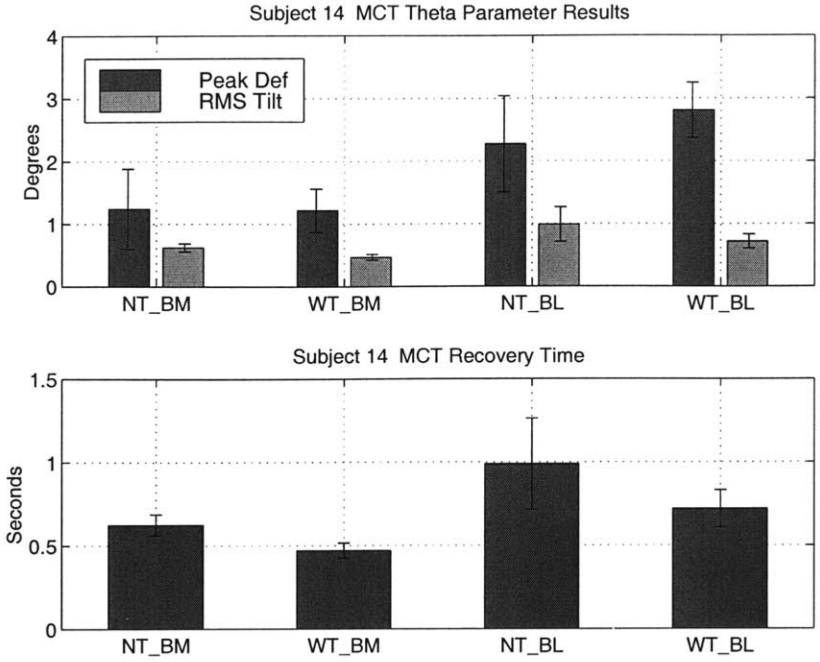


Figure D-13: **Subject 14 MCT Results.**

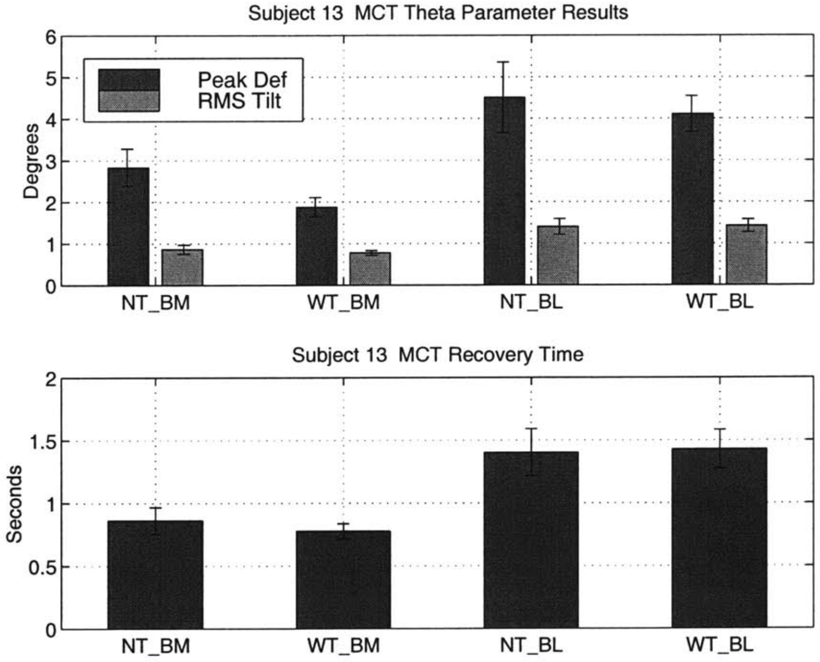


Figure D-14: **Subject 13 MCT Results.**

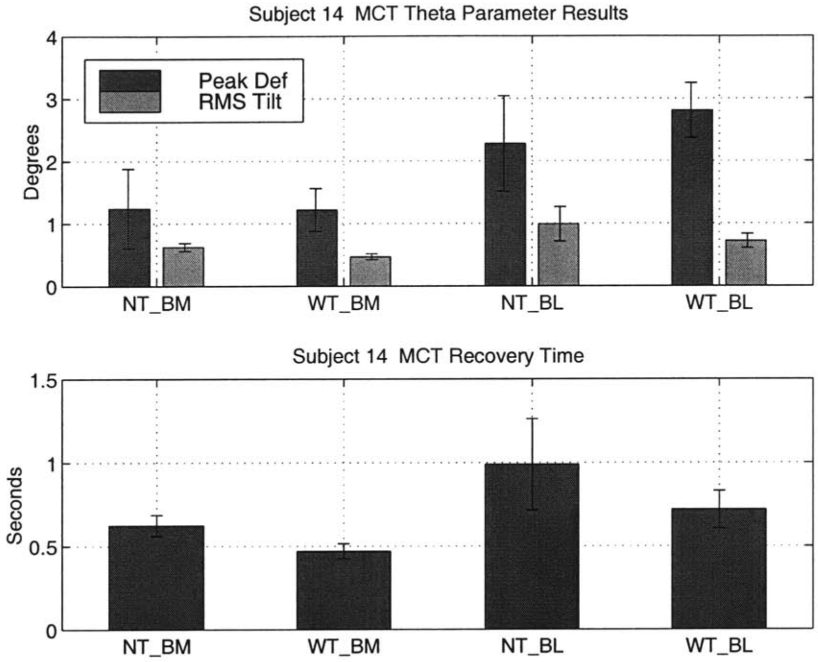


Figure D-15: **Subject 14 MCT Results.**

Appendix E

MCT COP Results

Note:

The error bars represent the standard error of each measurement.

X Axis Label	Definition
NT_BM	MCT Back Medium with No Tactors
WT_BM	MCT Back Medium With Tactors
NT_BL	MCT Back Large with No Tactors
WT_BL	MCT Back Large With Tactors

Table E.1: **Data Plot Key**

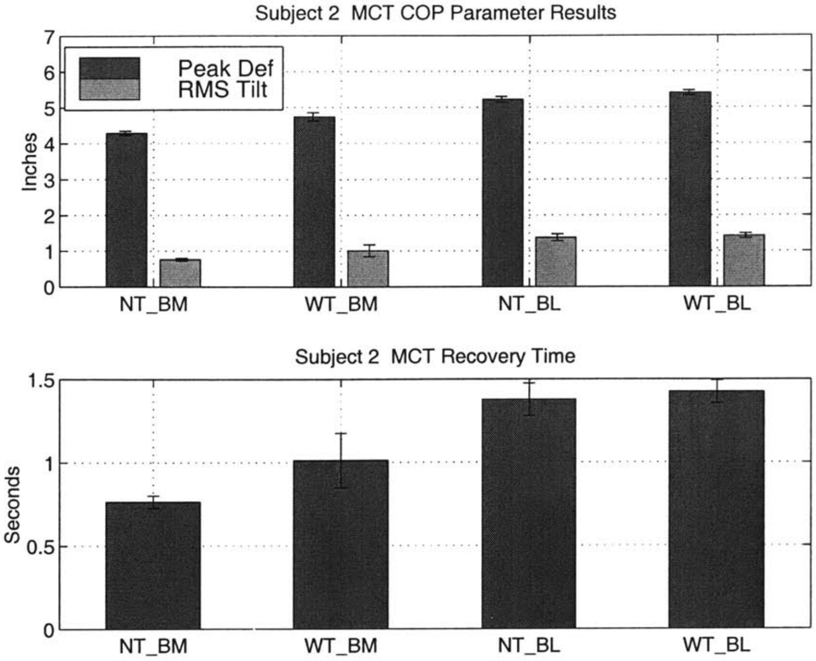


Figure E-1: **Subject 2 MCT Results.**

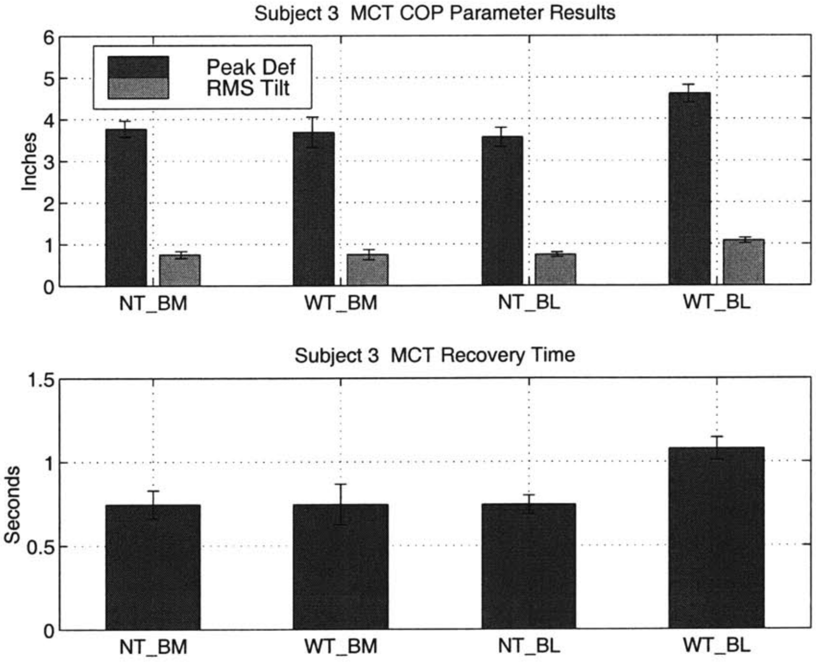


Figure E-2: **Subject 3 MCT Results.**

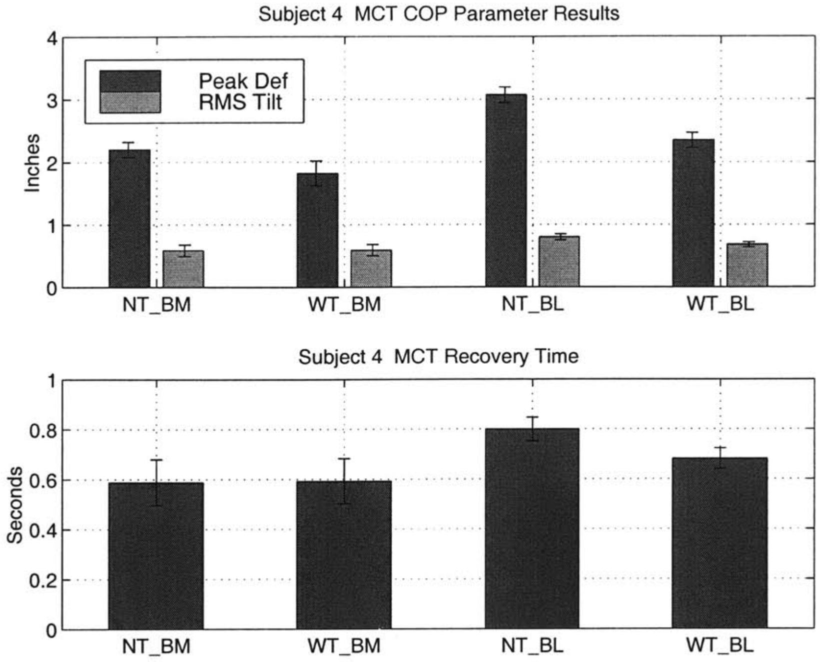


Figure E-3: **Subject 4 MCT Results.**

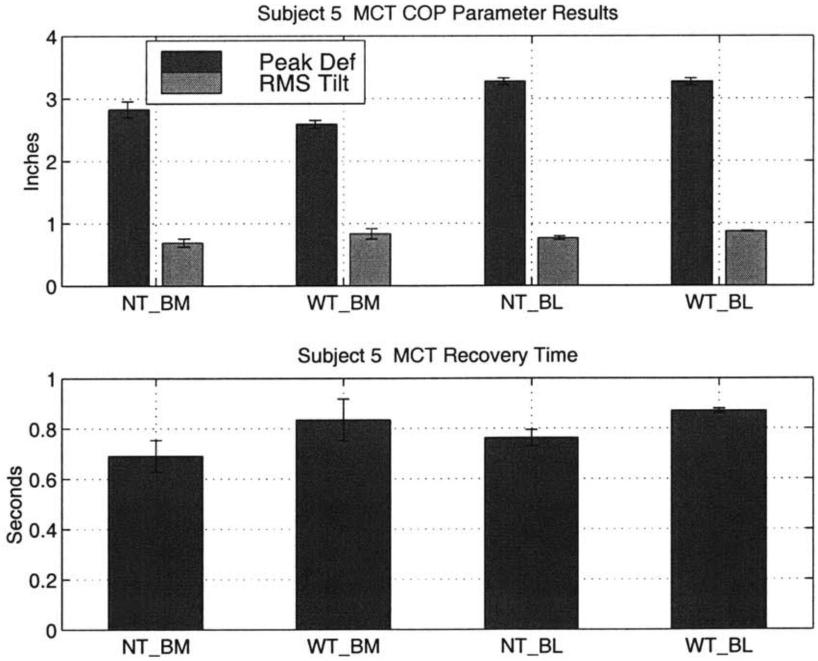


Figure E-4: **Subject 5 MCT Results.**

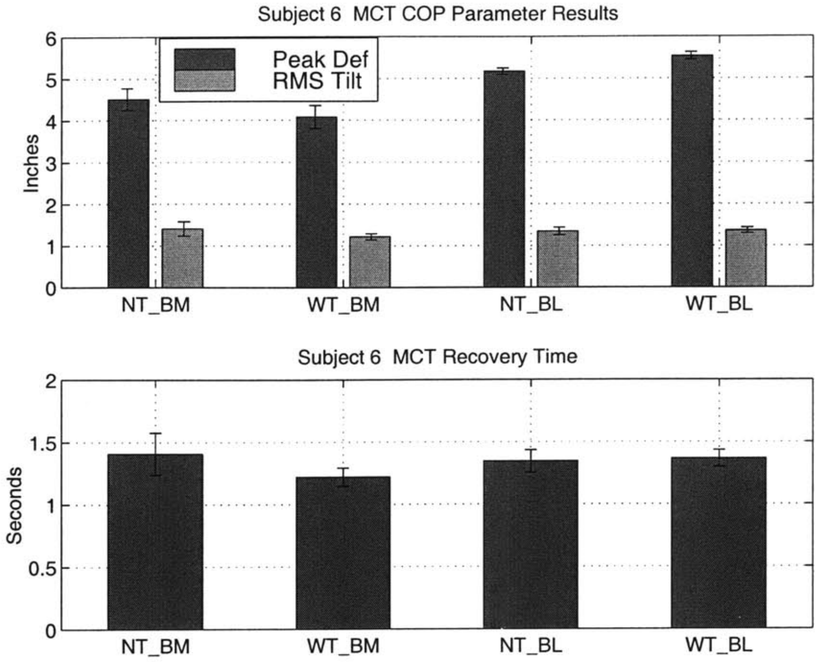


Figure E-5: **Subject 6 MCT Results.**

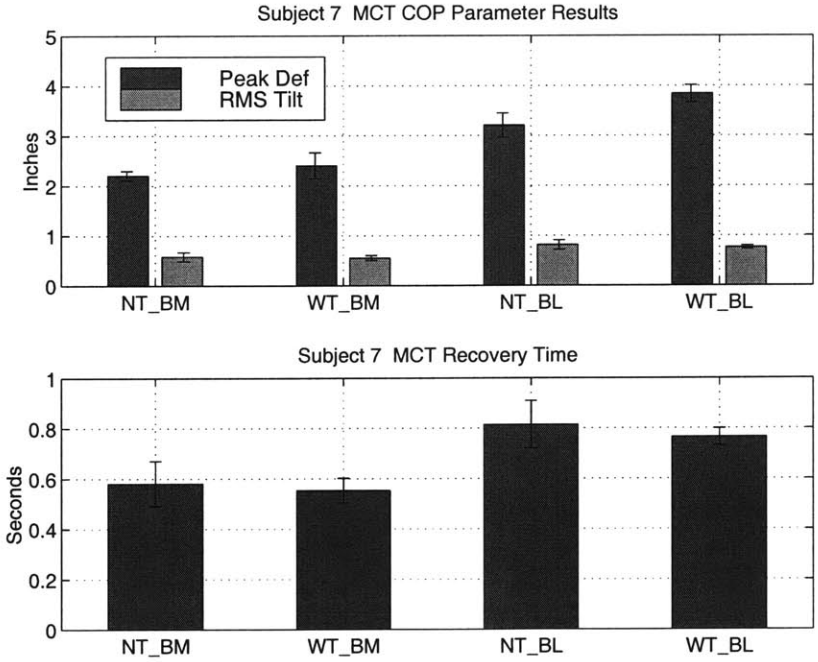
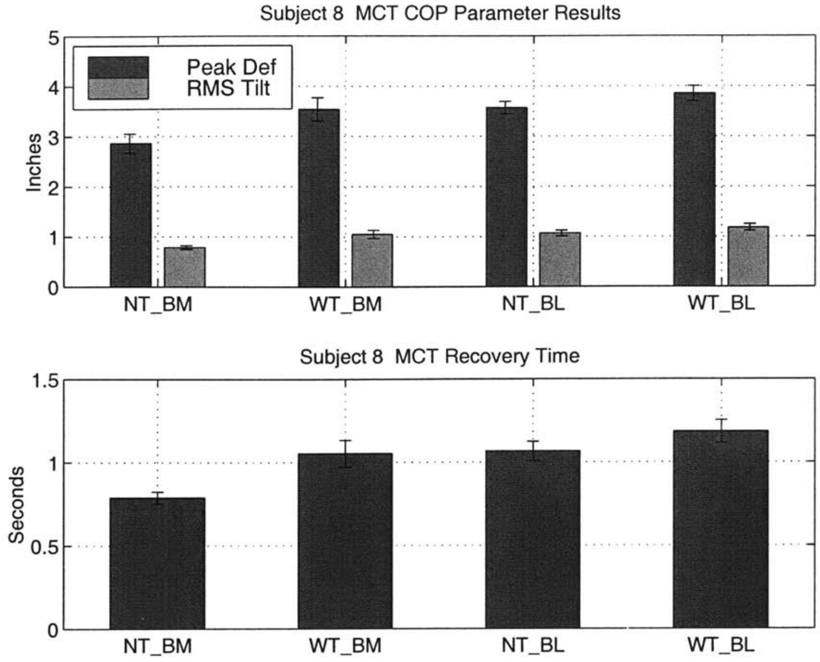
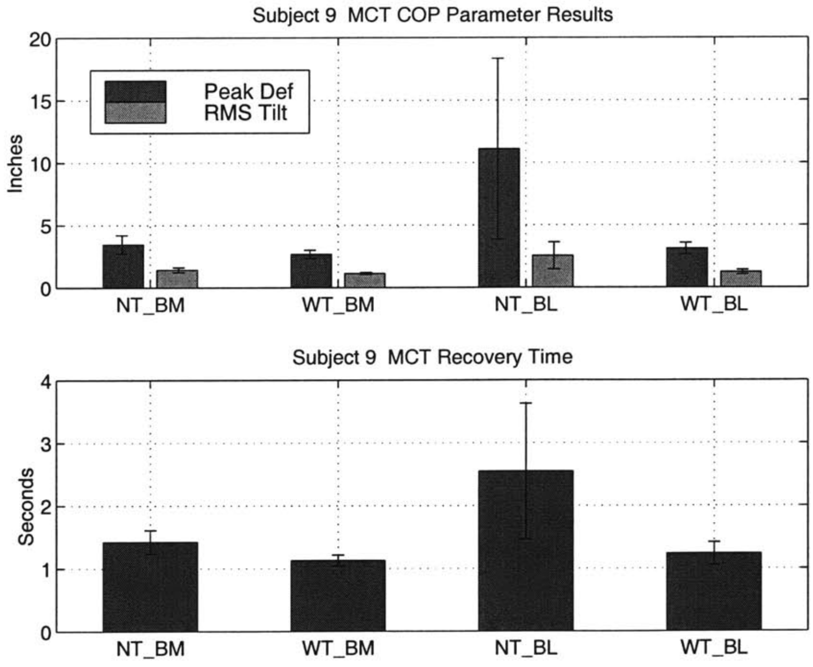


Figure E-6: **Subject 7 MCT Results.**


Subject 8 MCT COP Parameter Results

Subject 8 MCT Recovery Time

Figure E-7: **Subject 8 MCT Results.**


Subject 9 MCT COP Parameter Results

Subject 9 MCT Recovery Time

Figure E-8: **Subject 9 MCT Results.**

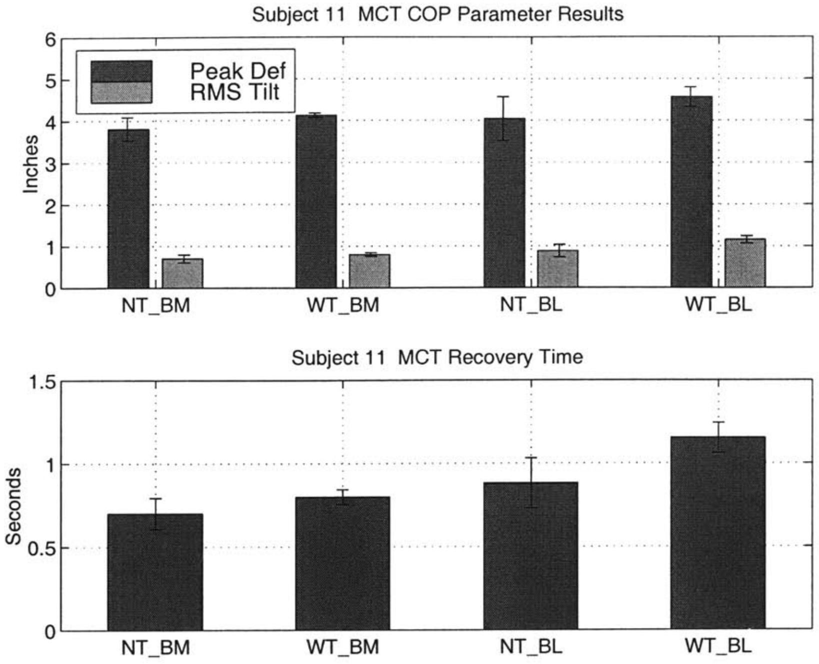


Figure E-9: **Subject 10 MCT Results.**

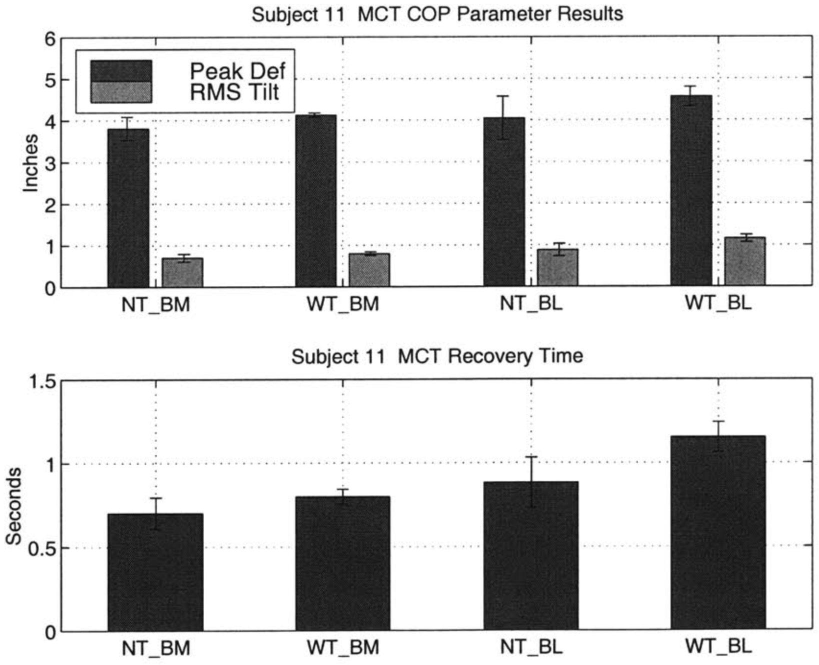


Figure E-10: **Subject 11 MCT Results.**

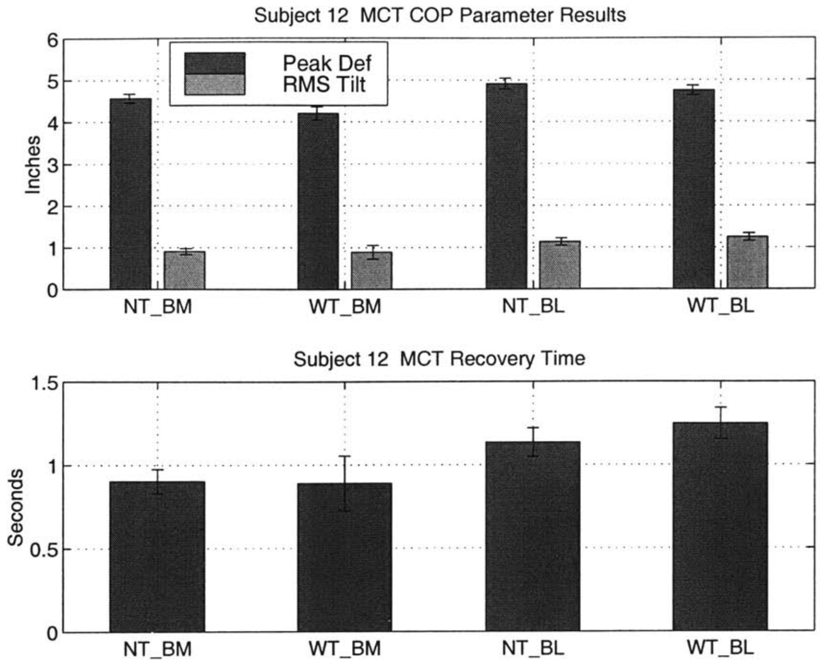


Figure E-11: **Subject 12 MCT Results.**

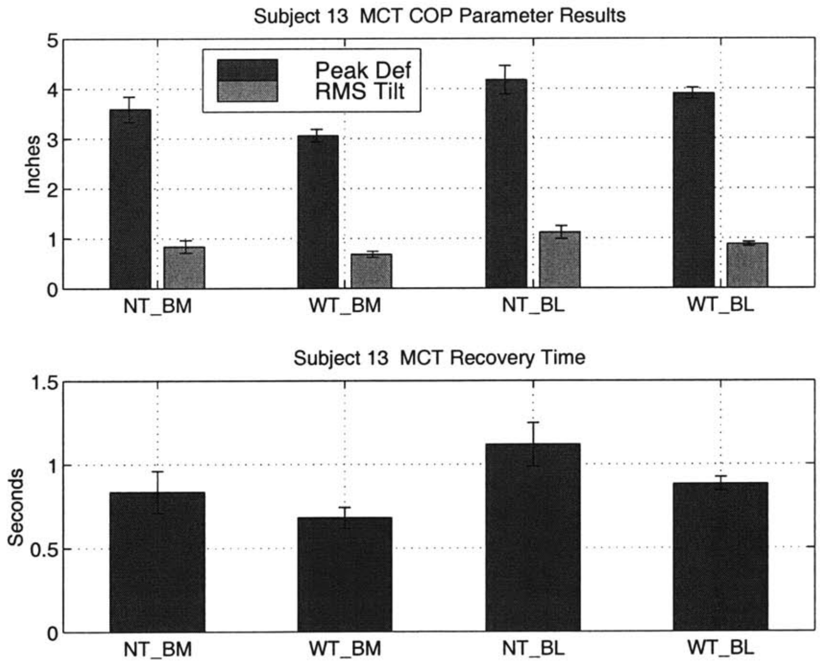


Figure E-12: **Subject 13 MCT Results.**

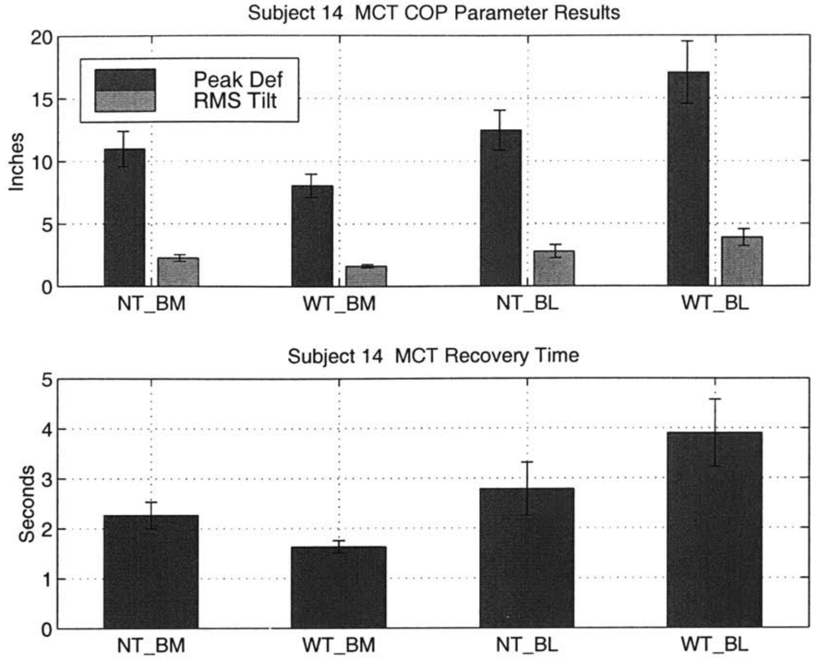


Figure E-13: **Subject 14 MCT Results.**

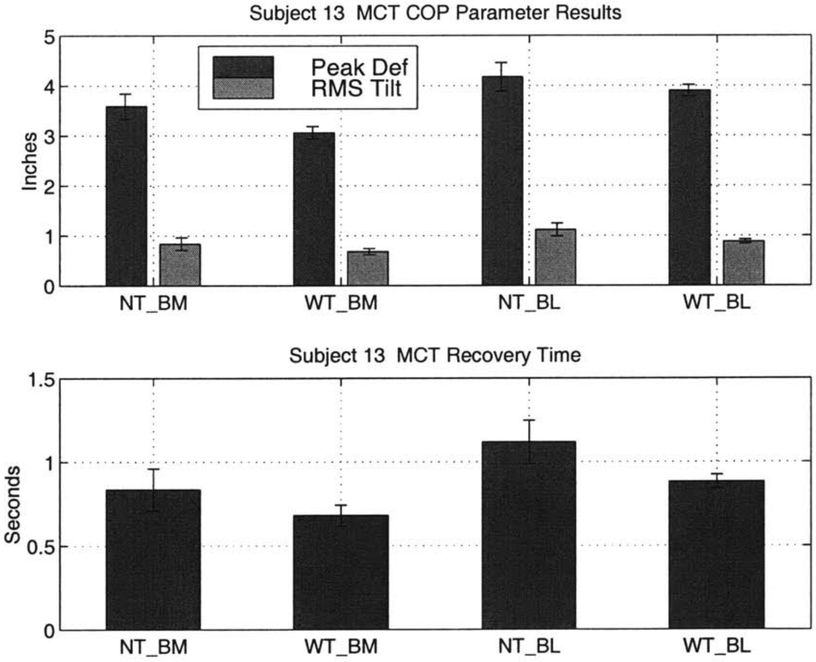


Figure E-14: **Subject 13 MCT Results.**

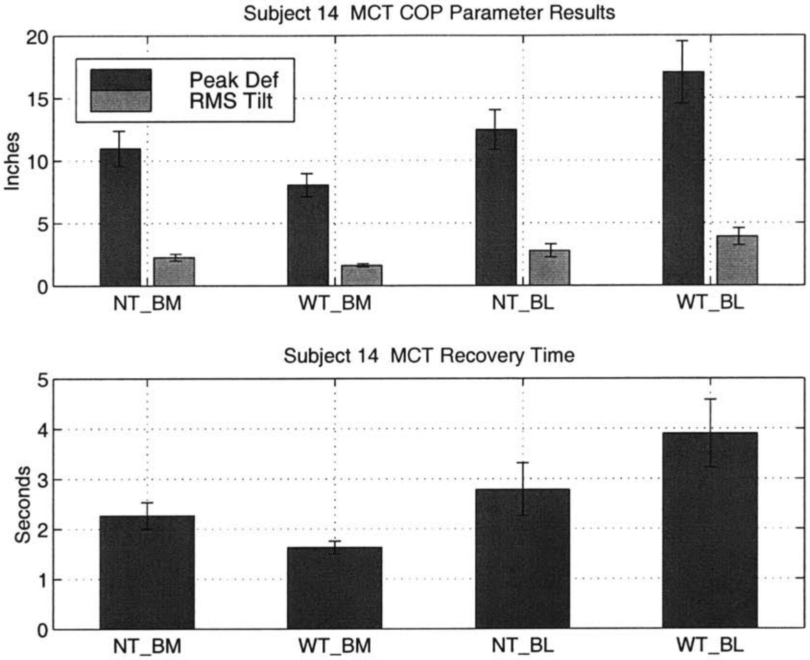


Figure E-15: **Subject 14 MCT Results.**

Appendix F

Matlab Scripts

F.1 SOT Matlab Scripts

```
%This script loads and saves raw SOT data.
I1 =input('What subject is the number?\n');
Heights
height=H(str2num(I1));
Temp1=[];Temp3=[];Temp4=[];Dpr_T=[];Dpr_R=[]; Dpr_M=[];Eq_T=[];
for i=1:4                    %loop for each test case
        for x=1:60           %loop for each test run
                if i==1
                        flname =['S',I1,'_NT_ST5_'];
                elseif i==2
                        flname =['S',I1,'_OT_ST5_'];
                elseif i==3
                        flname =['S',I1,'_NT_ST6_'];
                elseif i==4
                        flname =['S',I1,'_OT_ST6_'];
                end
                flname=[flname,int2str(x)];
                if exist(flname)>=1
                        Data    =load(flname);
                        [Dpr_T Eq_T]=SOT_load5(Data,height);
                        %SOT_load5 extracts the pertinent data from
                        %raw data files.

                        Dpr_R(x,:)      =[i,Dpr_T];
                        Dpr_M(x,:)      =[i,sqrt(var(Dpr_T))];
                else
                end
        clear Dpr_T Eq_T flname
```

```
        end
end

%**********Saving files
flname1=['S',I1,'_Main_Raw_Dpr'];
eval([flname1, ' = Dpr_R;']);
flname2=['S',I1,'_Main_Mean_Dpr'];
eval([flname2, ' = Dpr_M;']);
save(flname1, flname1)
save(flname2, flname2)





%**********************************************
%The following code is resposible loading SOT Data,
%calculating and means, standard errors, and running
%a paired t-test on the results

group1=[1,2,3,4,6,8,11,13,14];
n1=length(group1);
group2=[5,7,9,10,12];
n2=length(group2);

load Subj_Falls

k3=menu('reload data?', 'yes', 'no');
if k3==1
        for z=1:14
                flname1 =['S',int2str(z),'_Main_Mean_Dpr.mat'];
                if exist(flname1)>=1 & exist(flname2)>=1,
                        load(['S',int2str(z),'_Main_Mean_Dpr'])
                else
                        (['Could not find Subject  ', num2str(z)])
                        break;
                end
        end
else
end

k6=menu('What section of the data to should we compare?', 'First',...
                        'Last','Mean Substitution', 'Straight mean');

for h=1:2               %Group Loop
        if h == 1
                Results1=[];Results2=[];
```

```
        temp1=[]; temp2=[];
        Mean_Act=[];Stdev_Act=[];
        Fn_Data= [];
        group=group1;
        p=n1;
        'Group 1 Results'
elseif h == 2
        Results1=[];Results2=[];
        temp1=[]; temp2=[];
        Mean_Act=[];Stdev_Act=[];
        Fn_Data= [];
        group=group2;
        p=n2;
        'Group 2 Results'

end

for i=1:p
        z=group(i);
        eval(['Data1=S',int2str(z),'_Main_Mean_Dpr;'])
        Diff=[];DiffS=[];
        Data1(:,2)       =1 ./ Data1(:,2);
        Data1=fallinsert(0,z,Data1, falls);

        %***** Calculating Means and Standard errors**
        n1=length(Data1(:,1));
        D_Test1=[];D_Test2=[];D_Test3=[];D_Test4=[];

        for y=1:n1
                if Data1(y,1) == 1
                        D_Test1 =[D_Test1;Data1(y,2)];
                elseif Data1(y,1) == 2
                        D_Test2 =[D_Test2;Data1(y,2)];
                elseif Data1(y,1) == 3
                        D_Test3 =[D_Test3;Data1(y,2)];
                elseif Data1(y,1) == 4
                        D_Test4 =[D_Test4;Data1(y,2)];
                else
                end
        end

        means =[mean(D_Test1), mean(D_Test2),...
                mean(D_Test3), mean(D_Test4)];

        stdev =[std(D_Test1)/sqrt(length(D_Test1(:,1))), ...
               std(D_Test2)/sqrt(length(D_Test2(:,1))),...
               std(D_Test3)/sqrt(length(D_Test3(:,1))), ...
```

```
              std(D_Test4)/sqrt(length(D_Test4(:,1)))];

        Mean_Act =[Mean_Act  ;z,means];
        Stdev_Act =[Stdev_Act ;z,stdev];

        %***** Calculating Parameters *****
        [d1, d2] = find_diff(Data1, k6);
        temp1=[temp1;d1];
        temp2=[temp2;d2];

        Diff  =[Diff; mean(d1),mean(d2)];
        DiffS =[DiffS;std(d1)/sqrt(length(d1)),...
                std(d2)/sqrt(length(d2))];

        %***** Calculating Statistics *****
        [N, realt, hyp] =find_hyp(d1,2);
        Results1 =[Results1; z, N, realt, hyp];
        [N, realt, hyp] =find_hyp(d2,2);
        Results2 =[Results2; z, N, realt, hyp];

        if i == p
            [N, realt, hyp] = find_hyp(temp1,2);
            Results1=[Results1;0, N, realt, hyp];
            [N, realt, hyp] = find_hyp(temp2,2);
            Results2=[Results2; 0,N, realt, hyp];
        else
        end
    end
end
```

F.2 MCT Matlab Scripts

```
%This function loads and saves MCT data

I1 =input('What subject is the number?\n');

Heights
height=H(str2num(I1));

Temp1=[];Temp2=[]; Temp3=[];Temp4=[]; Eq_T2=[]; Dpr_T2=[];

for i=1:4                   %loop for each test case
```

```
        for x=1:45
            if i==1
                fname =['S',I1,'_NT_MBM_'];
            elseif i==2
                fname =['S',I1,'_OT_MBM_'];
            elseif i==3
                fname =['S',I1,'_NT_MBL_'];
            elseif i==4
                fname =['S',I1,'_OT_MBL_'];
            else
            end

            fname=[fname,int2str(x)];
            if exist(fname)>=1
                Data    =load(fname);
                [Dpr_T Eq_T]=MCT_load2(Data,height,i);
                Temp3 =[Temp3;Dpr_T];;
                Temp4 =[Temp4;Eq_T];;
            else
            end
        clear Dpr_T2 Eq_T2 fname Dpr_T Eq_T
        end
end

%*****Saving files****
fname1=['S',I1,'_MCT_Raw_Dpr'];
eval([fname1, ' = Temp1;']);
fname2=['S',I1,'_MCT_Div_Dpr'];
eval([fname2, ' = Temp3;']);
fname3=['S',I1,'_MCT_Raw_Eq'];
eval([fname3, ' = Temp2;']);
fname4=['S',I1,'_MCT_Div_Eq'];
eval([fname4, ' = Temp4;']);

save(fname1, fname1)
save(fname2, fname2)
save(fname3, fname3)
save(fname4, fname4)

%**************************************************
function [Dpr_T2, Eq_T2] =MCT_load2(Data,height,ind)
%This function divides a complete MCT test
%into its three runs.

%Handling Tilt Estimate from Balance Prosthesis
Dpr_tilt =Data(11,:);
```

```
Dpr=-180*Dpr_tilt/pi;

%Handling Tilt estimate from Equitest Platform
Sync =Data(19,:);
Y=length(Sync);

LF =Data(26,:); LF =40*LF;
RR =Data(25,:); RR =40*RR;
SH =Data(21,:); SH =SH;
LR =Data(23,:); LR =40*LR;
RF =Data(22,:);RF =40*RF;

FV=LF+LR+RR+RF;
%Y axis centers of vertical force: The distance between
%vertical projection of COG and the X axis
PY = ((LF+RF)-(LR+RR))./FV;
Eq=4.2*PY;

%Dividing up the data
i=find(Sync>=2.5);
start1=i(1);
Sync2=Sync(start1+100:Y);
i2=find(Sync2<2.5);
term1=i2(1)+start1+99;

Sync2=Sync(term1+100:Y);
i=find(Sync2>=2.5);
start2=i(1)+term1+99;
Sync2=Sync(start2+100:Y);
i2=find(Sync2<2.5);
term2=i2(1)+start2+99;

Sync2=Sync(term2+100:Y);
i=find(Sync2>=2.5);
start3=i(1)+term2+99;

Sync2=Sync(start3+100:Y);
i2=find(Sync2<2.5);


Avg_Tilt=[]; New_T=[];Dpr_T2=[];Eq_T2=[]; New_T2=[];
for x=1:3
        eval(['st=start',num2str(x),';']);
                if st+500 > Y
                        New_T=zeros(1,501);
                        New_T(1:Y-st+1)=Dpr(st:Y);
                        New_T2=zeros(1,501);
```

```
                New_T2(1:Y-st+1)=Eq(st:Y);
            else
                New_T=Dpr(st:st+500);
                New_T2=Eq(st:st+500);
            end
        Dpr_T2=[Dpr_T2;ind,New_T];
        New_T=[];
        Eq_T2=[Eq_T2;ind,New_T2];
        New_T2=[];
end
return;

%**************************************************
%This script calculates the parameters and statistics for MCT data.

k6=menu('What Section of data should we use?', 'First',...
        'Last','Mean Substitution', 'Straight mean');
for h=1:2                           %group Loops
    if h == 1
        group=[2,3,4,6,8,11,13,14];
        p=length(group);
        'Group 1 Results'
    elseif h == 2
        group=[5,7,9,10,12];
        p=length(group);
        'Group 2 Results'
    end

    Mdiff=[];Ediff=[];Ddiffs=[];Ediffs=[];
    for k1=1:3                      %Loop for each parameter
        Results1=[]; Results2=[]; Results3=[];
        temp1=[]; temp2=[];temp3=[]; temp4=[]; Fn_Data=[];

        for i=1:p                       %Loop for each subject in a
group
            z=group(i);
            eval(['Data1=S',int2str(z),'_MCT_Div_Dpr;'])
            eval(['Data2=S',int2str(z),'_MCT_Div_Eq;'])

            %Calculating the parameters
            if k1 == 1                          %Recovery time
                diffm1=finddecay(Data1);
                diffm2=finddecay(Data2);
            elseif k1 == 2                      %Peak Deflection
                diffm1=findmax(Data1);
                diffm2=findmax(Data2);
            elseif k1==3                    %RMS
```

```
            diffm1=findrms(Data1);
            diffm2=findrms(Data2);
        else
        end

        if z == 2
            [d1, d2] = findmn_dif2(diffm1, k6);
            [d3, d4] = findmn_dif2(diffm2, k6);
        else
            [d1, d2] = find_diff(diffm1, k6);
            [d3, d4] = find_diff(diffm2, k6);
        end

        temp1 =[temp1;d1]; temp2=[temp2;d2];
        temp3 =[temp3;d3]; temp4=[temp4;d4];

        Ddiff =[Ddiff;mean(d1),mean(d2)];
        Ediff =[Ediff;mean(d3),mean(d4)];

        Ddiffs =[Ddiffs;std(d1)/sqrt(length(d1)),...
            std(d2)/sqrt(length(d2))];
        Ediffs=[Ediffs;std(d3)/sqrt(length(d3)),...
            std(d4)/sqrt(length(d4))];

        [N, realt, hyp]  =find_hyp(d1);
        [N2, realt2, hyp2] =find_hyp(d2);
        Results1 =[Results1; z,N, realt, hyp,realt2, hyp2];

        [N, realt, hyp]  =find_hyp(d3);
        [N2, realt2, hyp2]  =find_hyp(d4);
        Results2  =[Results2; z,N, realt, hyp,realt2, hyp2];

        if i == p
            [N, realt, hyp] = find_hyp(temp1);
            [N2, realt2, hyp2] = find_hyp(temp2);
            Results3=[hyp, hyp2];

            [N, realt, hyp] = find_hyp(temp3);
            [N2, realt2, hyp2] = find_hyp(temp4);
            Results3=[Results3; hyp,  hyp2];
        else
        end
    end
Fn_Data=[Results1(:,1), Results1(:,4), Results1(:,6),Results2(:,4),Results2(:,6);...
    0, Results3(1,1),Results3(1,2),Results3(2,1),Results3(2,2)]

    end
```

```
end
```

F.3 Other

```
function [n1, realt, hyp] = find_hyp(diffm, test)
%This function runs a matched paired t-test.
%diffm =a vector containing all the differences
%       of the parameter to be tested.
%test  =determines whether the t-test rejects the null
%       hypothesis if the actual t value is greater than a
%        a deviation (test=1) or less than a deviation (test=2)


n1=length(diffm);
hyp=[];realt=[];dev=[]; sq_dev=[]; t=0;
%t values
T=[1,6.314; 2,2.920; 3,2.353;4,2.132;5,2.015;6,1.943; 7, 1.895;...
            8, 1.860; 9,1.833; 10,1.812; 11,1.796;...
            12,1.782; 13, 1.771; 14,1.761];
mn_diff=mean(diffm,1);
for i=1:n1
       dev          =[dev;diffm(i)-mn_diff];
end
sq_dev=dev.^2;
sum_dev =sum(sq_dev,1);
s=sqrt(sum_dev/(n1-1));
sd=s/sqrt(n1);

if n1-1 <= 14
       t=T(n1-1,2);
       realt=mn_diff ./ sd;
```

```
    if test == 1
        nrange=abs(mn_diff) - (t*sd);
        if realt > t
            hyp=1;
        else
            hyp=0;
        end
    else
        nrange=mn_diff + (t*sd);
        if realt < -t
            hyp=1;
        else
            hyp=0;
        end
    end
else
    realt= mn_diff ./ sd;
    hyp=nan;
    t=1.66;
    if test == 1
        nrange=abs(mn_diff) - (t*sd);
        if realt > t
            hyp=1;
        else
            hyp=0;
        end
    else
        nrange=abs(mn_diff) + (t*sd);
        if realt < -t
            hyp=1;
        else
```

```
            hyp=0;
        end
    end
end
return;
```

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