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# Evaluation of postural stability using sensory organization test

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## **ABSTRACT**

### **EVALUATION OF POSTURAL STABILITY USING SENSORY ORGANIZATION TEST**

**by  
Tiffany Sims**

Poor postural stability of the elderly and other patients has been a major concern. The cost of treating injuries due to poor stability is expected to rise to \$32.4 Billion by 2020. Many interventions have been proposed and used to improve stability. In order to determine the efficacy of these interventions, an objective evaluation of postural stability before and after intervention is important.

The aim of this thesis was to scientifically analyze the ambiguities in the equilibrium score (ES) given by the Neurocom Smart Equitest (NSE) machine, and compare it to a new measure of stability that has been proposed by Chaudhry et al., (2003) the postural stability index (PSI). This was done by determining the correlation of PSI and ES between the average sway angle, the ankle stiffness, and the SF-36 summary scores. Another aim was to investigate a method of validating mathematical models of the postural system, with the help of Ascension's Flock of Birds (FOB). This was done by testing the position output of the FOB in the NSE environment.

It was found that the average sway angle and ankle stiffness correlates better with the PSI. However, the SF-36 summary scores correlates better with the ES although both have poor correlation. It was also found that the FOB had a maximum error of 2.5 inches over a height range of 15.5 to 40.5 inches.

**EVALUATION OF POSTURAL STABILITY USING  
SENSORY ORGANIZATION TEST**

**by  
Tiffany Sims**

**A Thesis Submitted to the Faculty  
of The New Jersey Institute of Technology  
in Partial Fulfillment of the Requirements for the Degree of  
Master of Science in Biomedical Engineering**

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**January 2004**

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**APPROVAL PAGE**

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SENSORY ORGANIZATION TEST**

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This thesis is dedicated to  
my parents,  
Bernadine Mitchell and Harold Sims

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## NOMENCLATURE OF EQUATIONS IN TEXT

$A$	ankle joint
$M$	mass of body above ankle
$m$	total mass of the feet and the force plate
$d$	distance from vertical force transducers to the pin axis
$e$	distance from horizontal force transducers to ankle joint
$a$	distance from the line through ankle and pin joints to the center of mass of the feet
$h$	distance from ankle joint to the center of mass of the body
$F_{H,A}$	horizontal force acting at ankle joint
$F_H$	horizontal ground reaction force measured with force transducer at pin joint of the force plate
$F_V$	vertical force acting at ankle joint
$F_F, F_R$	vertical ground reaction forces measured with front and rear force transducers respectively
$\tau, \tau_g$	moment acting at ankle joint by muscles and by gravity respectively
$\theta, y$	absolute sway angle and center of mass with respect to fixed vertical reference
$\theta_m, y_m$	relative sway angle and center of mass with respect to line perpendicular to force plate
$\phi$	rotation angle of the force plate during sway-reference motion
$I, I_C$	subject's moment of inertia about its ankle joint and about its center of gravity

# CHAPTER 1

## INTRODUCTION

### 1.1 What is Postural Stability?

Human postural control during upright stance is typically evaluated in either of two modes. The first mode is quiet stance, or stance with no intended movement. The second mode is perturbed stance, which is quiet stance that is disturbed by an external perturbation, such as a push or a sudden shift of the support surface (a “dynamic” condition) (Collins, et al., 2003). Postural steadiness is the ability to remain close to the equilibrium point when no perturbations are experienced (Prieto, et.al.,1993). Postural stability is the ability to return the body close to the equilibrium point after being perturbed. The human body’s balance is maintained by a control system referred to as the balance or postural control system. It is believed that postural control is coordinated by the proprioceptive, vestibular, and motor systems. The proprioceptive system collects positional information from proprioceptors located in muscles, tendons, and ligaments that surround joints while the motor system outputs positional information.

The three key systems that the sensory organization test (SOT) studies are the somatosensory, vestibular, and visual systems. The somatosensory system (which gets information from the sense of touch and the proprioceptive system) provides information about vertical orientation relative to a support surface such as the floor, or in the case of this study the force plate. The

vestibular system provides both static and dynamic position using the relationship with our head and gravity. The sensory receptors for the vestibular system are located in the inner ear. The visual system also aids in postural control via peripheral vision, which provides information about either the motion of the subject or the motion of some other object (Bradley, 2002).

The ability to maintain posture can be reduced due to aging or pathologies such as stroke, head injury, or cerebral palsy. These pathologies affect balance by impairing either the proprioceptive or the motor systems. This in turn can reduce the postural stability of a person resulting in increased body sway and/or altered movement strategy. Typically, the movement strategy for controlling the antero-posterior sway is an ankle strategy, in which the body pivots around the ankles to maintain stability (Duarte, 2003). If the stability is somehow disturbed, the body reverts to a hip or step strategy in order to help maintain stability (Frykberg, 2000).

### **1.2 Why is Evaluation of Postural Stability Important?**

According to the National Center for Injury Prevention and Control, every hour an older adult dies as the result of a fall. Adults with impaired strength, mobility, balance and endurance are twice as likely to fall as healthier persons of the same age (Body sway measurement with PowerLab, 2002). Currently, devices such as the adjustable Klenzac ankle joint with a rigid plastic molded brace are being used to help patients gain balance. In order to know whether an

individual's balance has improved as a result of a particular intervention, the stability needs to be evaluated objectively, not on an individual's subjective report.

### **1.3 Evaluation of Postural Stability**

#### **1.3.1 Parameters to be Studied**

Postural control is currently being studied using 'posturographic' recordings that are typically made with a force plate. The force plate is used to measure the deviations from the center of pressure (COP) caused by changes in the subject's center of gravity as he or she maintains balance. Two key parameters of interest are postural sway or body sway and ankle stiffness.

It is believed that the COP, which occurs mainly in the horizontal plane, contains a lot of information about postural stability. Presently, measures of the COP and the horizontal force components are used to quantify the body sway, but the vertical force component is usually not taken into consideration in this context. (Collins et al., 2003) Postural sway has been evaluated by many researchers by analyzing the time-varying coordinates of the COP obtained from the force plate. The analyses are usually limited to statistical measures of the COP and center of mass (COM) such as the standard deviation, the path length or the mean velocity of the COP. (Fykberg et al., 2000)

The ankle stiffness is another parameter that offers much information. This is because, as mentioned before, it is believed that most people pivot about

the ankles in order to maintain stability. The ankle stiffness of the patients can be obtained by finding the slope of the ankle moment vs. sway angle through linear regression. It is expected that as the ankle stiffness increases the postural stability will decrease.

In addition to the more specific measures of postural sway discussed, a survey known as the Short Form Health Survey (SF-36) is used to discuss postural stability. The SF-36 was developed by John Ware and consists of 36 questions on various aspects of a person's well-being and health. The SF-36 was designed for use in clinical practice and research, health policy evaluations, and general population surveys. The SF-36 includes one multi-item scale that evaluates eight health concepts:

- 1) limitations in physical activities as a result of health problems
- 2) limitations in social activities as a result of physical or emotional problems
- 3) limitations in usual role activities as a result of physical health problems
- 4) bodily pain
- 5) general mental health (psychological distress and well-being)
- 6) limitations in usual role activities because of emotional problems
- 7) vitality (energy and fatigue)
- 8) general health perceptions

The survey was constructed for self-administration by persons 14 years of age and older, and for administration by a trained interviewer (in person or by telephone). This survey has been widely administered in many diagnostic

populations resulting in development of norms within diagnostic groups and by age. It has also been incorporated in the Large Health Survey of Veteran enrollees with modifications made to the scoring of two domains, mental (emotional) role and physical functioning role.

### **1.3.2 Review of Tests Used to Determine Postural Stability**

In clinical practice, postural stability is commonly evaluated by self-report and in-person interview/assessment instruments such as an activity-specific balance confidence scale (Powell et.al.,1995) , falls efficacy scale (Tinetti et.al.,1990), modified falls efficacy scale (Cheal et.al.,2001) , medical outcomes study short form 36 (SF-36) or functional tests such as Berg balance scale (Berg et.al.,1992).

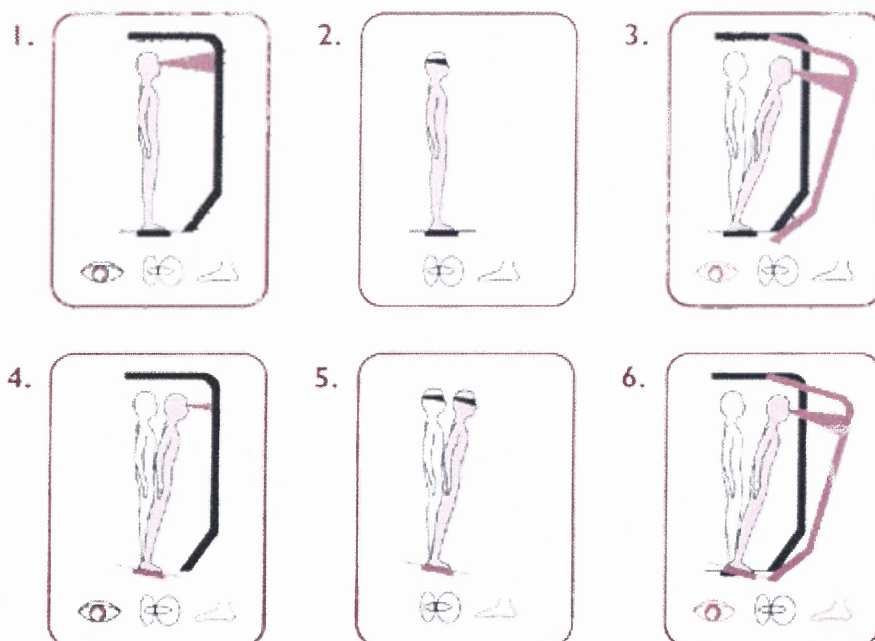
Functional tests are tests that have been designed to assess balance capabilities for various tasks related to everyday life. This section includes a few examples of functional tests currently used. When therapists perform an initial balance screening, they usually include an assessment of tandem (two legs placed one behind another) and one leg stance, which is called a stationary balance test. These evaluations are typically performed with shoes on, shoes off, and they may sometimes include tests on unstable or uneven surfaces. In addition to this, there may be a test with high heels on for women. The performance is quantified by the length of time the patient is able to maintain the stance, as well as a score for the amount of sway observed. A score of 1 is given if a normal amount of sway is observed and a score of 0 is given if an

excessive amount of sway is observed or if the sway was abnormal or asymmetric (Bradley,2002). Two trials are typically done for each case, and usually the best of the two scores is used for future comparisons. In order to determine if a patient's scores are within a normal range, the scores are to be compared to average scores of several normal subjects. It is important to note that scores do differ for different age ranges.

The functional reach test is another test performed by therapist. This test assesses the patient's ability to lean forward as far as possible, while reaching at a 90° angle from the body. The test is performed while the patient is standing close to (but not touching) a wall, with feet shoulder's width apart. This test is quantified by measuring the fingertip distance the patient successfully reaches. The farther a patient can reach, the better the postural control is said to be (Bradley, 2002).

Physical therapists also use a test that assesses the functional balance of patients, called the functional balance test. This test is a collection of 14 different static and dynamic tasks that vary in difficulty of maintaining balance. These test involve reaching, bending to pick up an object, standing on one leg, standing heel to toe, etc. Each task is assigned a score from 0 to 4 with 0 being the worst and 4 perfect, and all scores are summed together (Bradley,2002).

### 1.3.3 Sensory Organization Test



**Figure 1.1** Sensory organization test conditions.

Another test used by therapists to assess postural stability is the sensory organization test (SOT). The SOT was designed to identify abnormalities in the use of the somatosensory, visual and vestibular systems, the three systems that contribute to postural control. This is done by providing the eyes, feet and joints with inaccurate information. Whenever a normal individual experiences a conflict in one or more senses, an adaptive response occurs in which the individual suppresses or ignores the responses from those senses and selects more accurate sensory systems to generate the appropriate motor response. Abnormal individuals, on the contrary, find difficulty suppressing the inappropriate



responses from the senses and/or selecting a more accurate sensory system (Bradley, 2002).

This test simulates conditions that are similar to problems that people come across daily, for instance: (1) diminished visual cues, such as darkness, or lack of contrast or depth cues, (2) unstable or compliant surfaces such as a sandy beach, gravel driveway, or boat deck, or (3) conflicting visual stimuli which can be present in a busy shopping mall, or with large moving objects such as a moving bus (Neurocom, 2003). It is during this time that it is important for the body to determine which system is providing inaccurate information and choose the appropriate system.

The six different sensory conditions of the SOT can be administered without a force plate, or using a posturography testing system (force plate), as done in this study. These conditions are designed to manipulate the visual or somatosensory system. The test without the force plate is also known as the foam and dome test. In this test, a square piece of high-density foam is placed under the feet of the patient to reduce the effective use of the somatosensory system. In addition, a dome constructed from a round paper lantern is placed over the patient's head to distort visual information about body sway. The testing conditions are as follows: (1) plain upright stance, (2) blindfold, (3) dome, (4) foam, (5) foam & blindfold, (6) foam & dome. Each condition is to be performed for thirty seconds. These tests are quantified using the length of time the patient was able to perform each condition, and a score representing the amount of

sway. The amount of sway is measured relative to the limits of stability, which are the maximum distance a person can lean forward and backward without falling. A score of 1 is given if the patient stays within the limits of stability and a score of 0 is given if the patient exhibits abnormal, excessive or asymmetric sway (Bradley, 2002).

Sometimes a force plate is used to measure how well the patient can maintain their postural stability. The Neurocom Smart Equitest machine quantifies postural stability by using what is called the equilibrium score, which will be discussed more in detail later. In this case, inaccurate information is introduced through sway referencing the visual surround and force plate under the following six conditions:

**Table 1.1** SOT Conditions

CONDITION	PLATFORM	SURROUNDINGS	EYES
1	FIXED	FIXED	OPEN
2	FIXED	FIXED	CLOSED
3	FIXED	MOVING	OPEN
4	MOVING	FIXED	OPEN
5	MOVING	FIXED	CLOSED
6	MOVING	MOVING	OPEN

The patient's ability to use input from the somatosensory system to maintain balance can be evaluated using the ratio of condition 2 to condition 1. The patient's ability to use input from the visual system to maintain balance can be evaluated by using the ratio of condition 4 to condition 1. The patient's ability to use input from the vestibular system to maintain balance can be evaluated by using the ratio of condition 5 to condition 1 (NeuroCom, 2003).

For certain tests the force plate or visual surround moves using sway referencing, meaning that the motion of the force plate and visual surround follows the subject's motion. This is done to deliver inaccurate visual or proprioceptive information to the subject, which in turn causes the subject to rely more on other senses in order to maintain balance. It is possible to assign a gain factor for the sway any value from  $-2$  to  $2$ . A gain factor of  $-2$  would mean the machine would sway twice as much as the subject in the opposite direction the subject swayed. And a gain factor of  $2$  would mean the machine would sway as twice as much as the subject in the same direction the subject swayed. For all of the tests performed for this thesis, the sway referencing had a gain setting of one, meaning sway of the visual surround and the sway of the force plate followed the subject's sway exactly.

#### **1.4 Quantifying Postural Stability**

It is desirable for physicians to have a number or at least a small set of numbers that represents the postural stability of a patient. Although the tests previously mentioned each test important aspects of balance, they all (with the exception of the SOT with the force plate) contain a subjective score. What one therapist considers being normal sway, reach, etc. may not be considered normal by another therapist. Therefore, it is desirable to obtain more quantitative measures in their places.

Researchers have used several methods, including the equilibrium score to assess postural stability. One method involves measuring the rate at which

consecutive peak values of the total angular moment of all body segments about the ankles diminish when a standing person undergoes different types of perturbations (Alexander, 1992) (Shepard, 1993). This method, however, still does not provide a defined measure of postural stability. Another method involves identifying stability zones in a patient. The stability zones to be identified by the physician were the high preference, low preference, undesirable, and unstable zones. However, it is difficult for physicians to identify these zones (Popovic.et.al.,2000). It is desirable for physicians to have simpler methods to obtain a single number or small set of numbers to quantify stability.

#### **1.4.1 Equilibrium Score**

The equilibrium score (ES) was designed to indicate how well the patient's sway remains within the expected angular limits of stability during each sensory organization test trial. These limits of stability are determined by having normal subjects stand with the medial malleolus of each ankle directly above the y-axis zero position on the force plates. Their feet are placed an equal distance on each side of the x-axis zero position. They are then asked to lean forward and backward as far as they can without losing balance. The maximum forward and backward sway angles ( $\theta$ ) are calculated using formulas that will be discussed later (Figure 3.1).

Based on these experiments the limits of stability of normal subjects were found to be 7 degrees anteriorly and 5 degrees posteriorly relative to the center of base support. It is important to note that the equilibrium score does not take

this asymmetry into consideration. The average maximum sway for a normal person is considered to be 12.5°, although this angle may vary depending upon the age, sex, mass and height of the individual. The machine using the following formula calculates the equilibrium score (Neurocom International, 2001).

$$Equilibrium = \frac{12.5^\circ - (\theta_{max} - \theta_{min})}{12.5^\circ} * 100 \quad (1.1)$$

Therefore, persons with little sway would get scores close to 100 and persons with much sway would get scores close to 0. If a person falls during the trial, the operator interrupts the trial and the trial is assigned a score of 0. However, since the limits of stability vary from person to person, those with a limit greater than 12.5 , for example 13 degrees, will receive a negative score (i.e. 12.5 - 13= -.05). In such cases, the patient is assigned a score of zero, a practice that can eliminate useful information.

In addition to reporting equilibrium scores for each condition, the Neurocom Smart Equitest also reports a composite equilibrium score. This score is a weighted average of all the equilibrium scores calculated as follows:

$$Composite\_ES = \frac{mean(trial\_1) + mean(trial\_2) + \sum remaining\_conditions}{14} \quad (1.2)$$

If a subject does not complete any of the trials for a given condition, the denominator is reduced to reflect the number of elements in the numerator. This score is meant to describe the person's overall level of stability, and is the score generally used to study the person's stability over time.

A disadvantage of this score is that many combinations of anterior and posterior sway across the same overall range can give the same ES. For example, the overall limit of stability of 6 degrees can be made up of the many combinations. For example, 6 degrees of anterior sway and 0 degrees of posterior sway, or 3 degrees of anterior sway and -3 degrees of posterior sway, etc. All of these combinations would result in the same composite ES. Yet, assuming the average limits of stability a subject with +6/0 degrees of sway combination likely has a greater risk of falling than a subject with a 3/-3 combination. The first is close to the functional stability limit on the anterior side, whereas the second combination is not as close to the functional stability limit on either side. Therefore, the equilibrium score, which would be identical in these two situations, can be insensitive to functionally relevant differences in postural stability.

#### **1.4.2 Postural Stability Index**

Because the SOT-based ES does not take into account some key biomechanical aspects of postural stability and has many ambiguities as mentioned in section 1.4.1, a new measure of postural stability which is called the Postural Stability Index (PSI), was proposed (Chaudhry et al., 2003). A formula used to assess postural stability should include information such as the mass and height of the subject, as well as the ankle torque produced to maintain stability. These are absent in the formula for ES.

The Postural Stability Index is defined as the percentage ratio of the total stabilizing ankle torque and the total destabilizing torque due to gravity (obtained from the product of the weight, height and the sway angle). The lower of the two quantities is placed in the numerator. In mathematical terms, PSI is defined as:

$$PSI = \frac{\sum |Mgh\theta|}{\sum |\tau|} * 100 \quad \text{or} \quad PSI = \frac{\sum |\tau|}{\sum |Mgh\theta|} * 100, \quad (1.3 \& 1.4)$$

whichever is less than 100. The range of PSI is 0 to 100, and the amount of instability is reflected in how much the PSI is less than 100. When the numerator and the denominator are equal, the PSI is 100%, and the subject is perfectly stable.

Recall that two individuals with different magnitudes of anterior and posterior sway, but with the same overall sway range will have the same ES (see equation 1.1). However, it is believed based on the formula for PSI that the two individuals will have different PSI scores. This is because the PSI relies on biomechanical data recorded from each individual, whereas the ES relies heavily on normative assumptions. A composite PSI score was found for each test in a manner similar to that of the equilibrium score defined by the machine.

$$Composite\_PSI = \frac{mean(trial\_1) + mean(trial\_2) + \sum remaining\_trials}{14} \quad (1.5)$$

## **CHAPTER 2**

### **BACKGROUND REVIEW**

#### **2.1 Mathematical Models**

In addition to physically measuring the center of pressure, there have been many efforts to mathematically model the balance system. It is difficult to model the postural steadiness and stability of an individual, since there is no clearly defined input function. Nevertheless, researchers have modeled the control system to a reasonable amount of accuracy using the relations between body segment angles and the joint torques based on the mechanical structure of the body.

The inverted pendulum is the most common model used to describe postural control during quiet stance. However, the single-link inverted pendulum model of the body is most commonly discussed only in the Anterior/Posterior direction. In many cases a more complete two link inverted pendulum model is used to evaluate ankle joint stiffness. In these two-link models, the postural control is defined by the relation between the center of pressure and the center of mass. In addition, Firsov (1990) described a three link inverted pendulum model incorporating elasticity and damping coefficients for each joint.

Although the single-link, two-link, and three-link inverted pendulums are simpler models to use for analysis, they do not describe completely human postural dynamics at all the joints - ankles, knees, hips and the neck (Stockwell 1981, Levin 1998). This is supported by the findings that angular displacement, velocity and acceleration of the hip are significantly greater than those of the



ankle during quiet standing in humans (Aramaki, 2001). It is also observed (Deniskina & Levik, 2001) that the basic contribution to posture regulation in the frontal plane when standing is made by hip muscles. Four-link mathematical models that take into account, foot, shank, thigh, torso, and the force plate mass and motion have been developed. Zhiming et al. (2002) have developed a four-link model, that unlike the previous 1,2 and 3 link models, takes into account the horizontal component of the ground reaction. In almost all of the models described above, the role of viscous friction at the joints had not been evaluated. However, torque due to this viscous friction at the joints has been included in a four-link model developed by Zhiming et al. (see Appendix D).

## **2.2. Limitations on Current Devices**

Three dimensional camera systems are frequently used for motion analysis. Although this method is believed to be very promising and fairly accurate there are some disadvantages. These systems are expensive, only allow measurements in a restricted volume, and the markers are easily obscured from vision resulting in incomplete data (Kidder, 1996).

The accelerometer has been proven useful for motion analysis when larger motion is being observed. However, for this study patients will exhibit a small range of motion. Therefore, an accelerometer by itself will not be the best tool for our measurements.

There has been a device developed that uses both an accelerometer and a gyroscope (Mayagoitia, 2002). This system is less expensive and more portable. In addition to that, it has been found to yield comparable results to a commercially available camera system at lower speeds. Some of the disadvantages to this system are that in some instances it yields errors up to 15% and the device suffers from slippage which results in incorrect data.

Recently, researchers have started using electromagnetic tracking devices as a kinematic measuring tool. There have been studies conducted to determine the accuracy of such device over longer ranges and also when used in conjunction with a force plate. There have been concerns of how a force plate could possibly affect an electromagnetic tracking device. It has been found that these tracking devices in general yield errors less than 150 mm and 10° with a standard deviation less than 3mm for position and 0.3°. When the tracking device is used in conjunction with a force plate, it was found that results were satisfactory for sensors located at least 500 mm away from the force plate. It was also found that errors increased with the distance between the transmitter and the sensor and decreased with the distance between the force plate and the sensor (Perie, 2002).

The Flock of Birds is a device developed that allows the use of multiple electromagnetic tracking sensors at one time. This device has also been studied

for accuracy and it was found that it yielded smaller errors than the device studied by P'erie et al (Frykberg, 2000).

## CHAPTER 3

### DEVICES USED IN THIS THESIS

#### 3.1 Neurocom Smart Equitest Machine



**Figure 3.1** Neurocom Equitest Machine.

Source: <http://www.onbalance.com/neurocom/products/SMARTEquiTest.aspx>

##### 3.1.1 Mechanics

The Neurocom Smart Equitest system is composed of a platform base, a visual surround and a computer, printer and monitor system. The platform base is composed of a dual force plate, force transducers (each with its own amplifier), and servomotors. The dual force plate, one plate for the left foot and one plate for the right foot, is made up of two 9 inch by 18 inch footplates that are connected by a pin joint. The force plates are supported by four strain gauges that are mounted symmetrically on a supporting center plate. The strain gauges measure vertical forces applied to the force plate. Due to the pin joint that allows each plate to rotate freely, a different set of forces can be measured for each foot. There is a fifth transducer located directly beneath the center pin joint. This

transducer measures the shear forces, the forces in the plane parallel to the floor. This plane is considered the X-Y plane.

Before using the force plates, a subject is positioned so that the ankles are centered over a stripe that is printed on the force plate, with the feet an equal distance laterally from the center line. This allows their center of gravity to be located directly at the intersection of the X and Y-axes. The point at which the two axes intersect is called the electrical zero position and it serves as a reference point for the calculation of the sway angles.

The force plates are moved when commanded by the computer using dc servomotors, each powered by its own linear dc amplifier. These servomotors are attached to the force plate using lead screws and ball bearing nuts, a detail that will be of importance when using the flock of birds. With the use of ball bearing gears, 95% of the motor's power can be delivered to the force plate.

### **3.1.2 Calculations Made by the Equitest Machine**

There are five main force measures that the Equitest system either calculates or measures. The first is the total vertical force, which is the sum of the right front transducer (RF), the right rear transducer (RR), the left front transducer (LF) and the left rear transducer (LR). The second is the total horizontal force, which can be measured using the transducer located directly below the center pin joint. The third is lateral center of the vertical force ( $P_x$ ), which is considered to be the distance between the vertical projection of the patient's center of gravity and the Y axis. This distance can be calculated using the following equation:

$$P_x = \frac{(RF + RR) - (LF + LR)}{RF + RR + LF + LR} * 4.00in \quad (3.1)$$

The fourth and the fifth are the left and right centers of vertical force, which are considered to be the distance between the vertical projection of the patient's center of gravity and the X axis. These can be calculated using:

$$P_{yL} = \frac{LF - LR}{LF + LR} * 4.20 \quad P_{yR} = \frac{RF - RR}{RF + RR} * 4.20 \quad (3.2 \& 3.3)$$

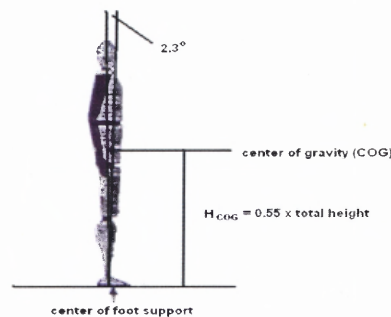
$$P_y = \frac{(LF + RF) - (LR + RR)}{LF + RF + LR + RR} * 4.20 \quad (3.4)$$

Most of the measurements made for this study are based on the center of gravity of the subject. Therefore, it is important to know how the Neurocom Smart Equitest determines this point. The Neurocom Smart Equitest actually measures the person's center of mass. Neurocom's definition of the center of mass is as follows: " the point in the object that moves the way a single particle of the same mass would move if equivalent external accelerations were applied to it". When the only acceleration applied to an object is gravity, the center of mass of that object is equivalent to that object's center of gravity. It has been found experimentally that the center of gravity of a person is located at 55.27% of the total height of that person, and 14% of foot length in front of the medial malleolus bone in the ankle joint. In terms of degrees the center of gravity of a person lies 2.3 degrees forward from a vertical line passing through the ankle joints (Neurocom International, 2001).

If we were to drop a vertical down from this theoretical center of gravity point while a person was standing vertically we would land on a point in the foot

that is called the center of foot support. It is about this point, that all sway angles have been determined. The anterior-posterior (AP) center of gravity sway angle is the angle between the vertical line described previously and the line passing through the current center of gravity and the center of foot support. The machine uses the following formula calculates the sway angle:

$$\theta = \arcsin\left(\frac{P_{COG}}{H_{COG}}\right) - 2.3^\circ \quad (3.5)$$



**Figure 3.2** Sway angle diagram.

Here,  $P_{COG}$  is the instantaneous PY, which is the horizontal distance between the X axis and the patient's center of gravity.  $H_{COG}$  is 55.27% of the person's height. The 2.3 degrees is subtracted because the center of gravity lies 2.3 degrees in front of the person's absolute vertical line.

For each condition, data is recorded for three 20 second trials, which are sampled at 100 Hz. The machine reports several scores from the SOT including the Equilibrium Score, the Initial Alignment, and Strategy Score. The Initial Alignment score indicates the person's initial center of gravity position before the start of each trial. The Strategy Score indicates whether the person uses their

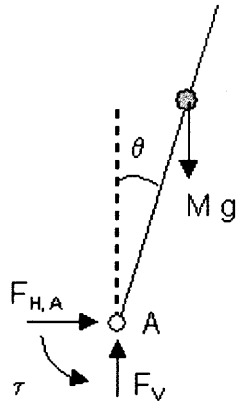
ankles or their hips more to maintain balance. The Equilibrium Score as mentioned before indicates the how well the patient's sway remains within the expected angular limits of stability during each SOT trial.

### **3.1.3 Need for Better Sway Angle Calculations**

The Neurocom Equitest machine mentioned earlier, provides the displacement of the center of mass (COM) which is calculated by taking 14 samples of the center of pressure (COP) and finding the moving average. These COP measurements are a result of only the vertical ground reaction force. In order to effectively evaluate muscle stiffness, COM data more accurate than the moving average of the COP is needed. With this in mind a new mathematical model of the center of mass of the postural system has been developed that includes the equations of motion in the horizontal and vertical directions as well as the moment equation (Zhiming et.al.,2002).

To develop this new model, the system equations of motion for the body must be defined first. These equations can be determined with the help of inverted pendulum model of the body mentioned earlier (Figure 3.2). In this figure, the body's center of gravity is denoted by the gray circle and the ankle is denoted by the white circle.





**Figure 3.3** Free body diagram of the inverted pendulum model of the body.

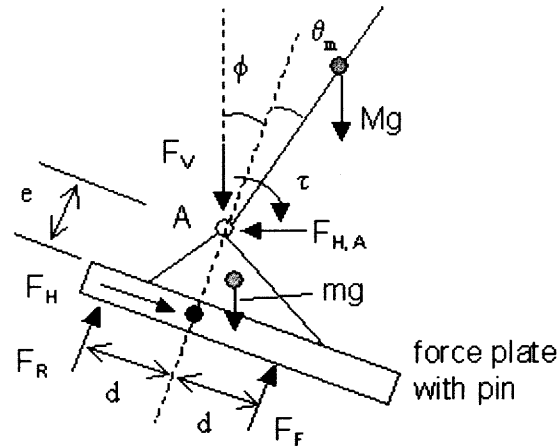
The equation of motion for the body can be written as

$$F_{H,A} = M \ddot{x}_c = M h(\ddot{\theta} \cos\theta - \dot{\theta}^2 \sin\theta) \quad (3.6)$$

$$F_V = M(g + \ddot{y}_c) = Mg - Mh(\ddot{\theta} \sin\theta + \dot{\theta}^2 \cos\theta) \quad (3.7)$$

$$-\tau + F_V h \sin\theta - F_{H,A} h \cos\theta = I_c \ddot{\theta} \quad (3.8)$$

Since it is possible to acquire the forces exerted by the feet onto the force plate, it is also important that the equations of motion for the feet are defined as well. This will allow the sway angles and torque to be found in terms of the data provided by the machine. The equations can be derived with the help of the schematic below (Figure 3.3). In this figure, the rectangle represents the force plate and the gray and white circles still represent the center of mass of the body and the ankle respectively.



**Figure 3.4** Free body diagram of the foot on the force plate.

The equations of motion for the feet can be written as:

$$F_{H,A} = F_H \cos\phi + (F_F + F_R)\sin\phi \quad (3.9)$$

$$F_V = (F_F + F_R)\cos\phi - F_H \sin\phi - mg \quad (3.10)$$

$$\tau - (F_F - F_R)d - F_H e + mga \cos\phi = 0 \quad (3.11)$$

It is important to remember that the platform is not always flat. For some of the cases the platform experiences sway referenced motion. In other words, the amount of rotation the platform experiences is represented by  $\phi$  and is equal to the sway angle of the body's center of mass,  $\theta_m$ , multiplied by a gain which can be set at anything from -1.0 to 2.0. For this study, the gain is set to 0 for the nonmoving platform and 1.0 for the moving platform. The absolute sway angle,  $\theta$ , which is with respect to the vertical, can be found by summing  $\theta_m$  and  $\phi$ . This definition of  $\theta$  differs from that of the Neurocom machine, which always takes  $\theta$  to be  $\theta_m$  (the COM sway relative to the platform). The disadvantage to the

Neurocom approach is that  $\theta_m$  does not always give a full picture of the amount of sway the patient is experiencing.

After combining the equations of motion for the body and the equations of motion for the feet and eliminating the forces ( $F_{H, A}$ ,  $F_V$ , and  $\tau$ ) that cannot be found using the force plate the final set of system equations can be found:

$$Mh(\ddot{\theta} \cos\theta - \dot{\theta}^2 \sin\theta) = F_H \cos\phi + (F_F + F_R) \sin\phi \quad (3.12)$$

$$Mh(\ddot{\theta} \sin\theta + \dot{\theta}^2 \cos\theta) = (M + m)g - (F_F + F_R) \cos\phi + F_H \sin\phi \quad (3.13)$$

$$I\ddot{\theta} = Mgh \sin\theta - (F_F - F_R)d - F_H e + mga \cos\phi \quad (3.14)$$

Using algebra and a small angle approximation,  $\theta$  and  $\tau$  can be found as given below.

To calculate the sway angle for conditions 1,2,and 3 the following formula should be used:

$$\theta = \frac{Mh[(F_F - F_R)d + F_H e - mga] + I \cdot F_H}{M^2 gh^2 - I[(M + m)g - (F_F + F_R)]} \quad (3.15)$$

To calculate the sway angle for conditions 4,5,and 6 the following formula should be used:

$$\theta = \frac{Mh[(F_F - F_R)d + F_H e - mga] + I \cdot F_H}{M^2 gh^2 - I \left[ (M + m)g - \frac{F_F + F_R}{2} \right]} \quad (3.16)$$

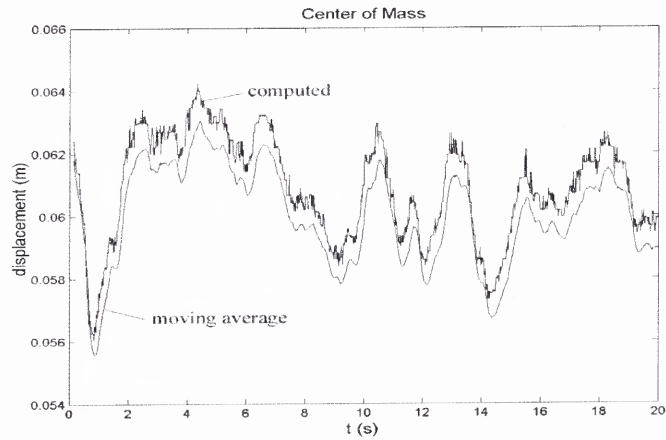
To calculate the ankle moment the following formula can be used:

$$\tau = (F_F - F_R)d + F_H e - mga \quad (3.17)$$

The position of the center of mass can be obtained by using equation 3.16.

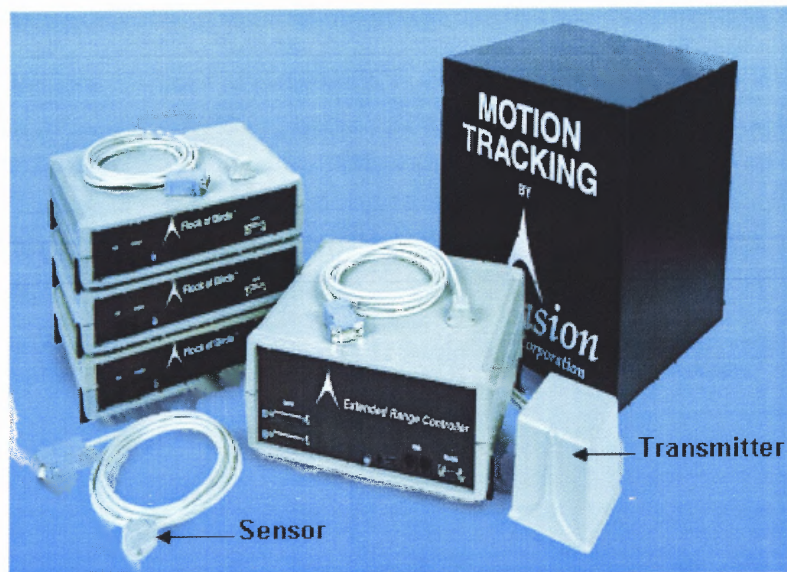
$$y = h * \sin\theta \quad (3.18)$$

An example of data calculated using both the old and new formulas for theta is shown below.



**Figure 3.5** COM data for a condition 1 trial.

### 3.2 Flock of Birds



**Figure 3.6** Flock of Birds system

Retrieved from <http://www.ascension-tech.com/products/flockofbirds.pdf>

### **3.2.1 Reason for Choosing Flock of Birds**

In order to gain more information about a person's stability, it would be helpful to know exactly what the hips, knees and other parts of the body do during the SOT. In order to do this, some other instrument must be used in conjunction with the Neurocom Smart Equitest System. There have been many instrument used over the years for motion analysis including camera systems, accelerometers, and various tracking devices but all have not returned results that would be accurate enough for this study.

Based on what has been found in the literature, it is believed the best system to use to measure the sway could be the Flock of Birds. Of all the other systems, this system has proven to be the best concerning reliability, cost and ease of use.

### **3.2.2 How the Flock of Birds Works**

The flock of birds is a six-degree of freedom measuring device that is designed to simultaneously track the position and orientation of multiple sensors. The system is composed of a transmitter that transmits a pulsed DC magnetic field to all of the sensors in the flock. Each sensor is able to make anywhere from 20 to 144 measurements per second. For this thesis, the recording rate was set to 60 measurements per second. It is important to note that for the system used in this study, the sensors should be within 4 feet of the transmitter in order to ensure accurate measurements.

The sensors are relatively light and are able to be placed almost anywhere. It is recommended that the sensors should only be mounted on non-metallic surfaces using non-metallic bolts. Care should also be taken to not mount the sensors near power supplies or any other low-frequency current-generating device, because the sensors may pick up these signals.

The transmitter, which is much heavier than the sensor, must be placed on a non-metallic surface as well. It is also recommended that the transmitter should only be placed or mounted on non-metallic surfaces using non-metallic bolts.

Since the Flock of Birds works on DC magnetic fields, one concern is that the Neurocom Equitest machine can cause interference either through the magnetic fields produced by the motors or through the metal on the force plate. There has been a study done by LaScalza et al., to see how metal and sampling frequency can affect the signal between the transmitter and receiver (LaScalza et al., 2003). In that study, a 5x5x15 cm block of steel and aluminum was placed 15 cm away from the transmitter in the x direction. The investigator chose six positions for testing. The test was conducted once with aluminum, once with steel, and once without metal. For each metal condition, measurements were taken at 20,60,100, and 140 Hz. It was found that the more the sampling rate increased the more the aluminum affected the accuracy of the measurements. Also, it was found that the more the sampling rate increased the less steel affected the accuracy of the measurements. Another study (Stone, 1996) was

discussed by LaScalza et al., which yielded slightly different results. It was mentioned that this discrepancy could be do to the fact that the other investigators tested the Flock of Birds in an environment composed of several metals. Since each laboratory setting will have different types and combinations of metal in their environment it was suggested that the flock be tested for accuracy in each laboratory setting.

It was still unknown, however, what effect can a force plate system have on the flock of birds. This question was partially answered by a study conducted by D. Perie et al. (2002). The purpose of this study was to determine the accuracy of an electromagnetic tracking device in an environment of a conventional force plate. The electromagnetic system that was chosen for this study was the Motion Star by Ascension Inc., this like the Flock of Birds is a DC tracking device. The device is composed of a long-range transmitter, a base computer and 12 sensors. Data was collected at a sampling frequency of 86.1 Hz for each sensor, simultaneously. The surface of the force plate was located at ground level and the transmitter center was located at 115 cm above the ground level and 75 cm from the nearest measured point. The investigator determined the error based on the distance between the transmitter and sensor as well as the distance between the force plate and sensor. It was found that there were no differences between data collected with the force plate switched on or off. Errors increased with the distance between the sensor and transmitter, and errors decreased with the distance between the sensor and force plate.

## CHAPTER 4

### THESIS OBJECTIVES AND METHODS

The ES that is provided by the Neurocom Smart Equitest device has been accepted to be a good measure of postural stability. However, the ES seems to have limited usefulness since it cannot be used to reasonably determine whether the ES value for an individual falls within the range for a particular diagnostic group. This is because it suffers from ambiguities (see section 1.4.1). More specifically, ES does not take into consideration the mass or height of an individual (Mgh), which is believed to provide much information about the ankle stiffness. For this reason an alternative measure, known as the postural stability index was introduced (Chaudhry et al., 2003). One of the goals of this thesis, is to study how well the machine's ES, the computed ES, and the PSI correlates with the two key aspects of balance (sway angle and ankle stiffness) mentioned earlier, and the SF-36. The second goal is to see if it is possible to validate the mathematical models mentioned earlier using the flock of birds.

#### 4.1. Comparing PSI and ES

In preliminary studies, it has been observed that veterans with medically unexplained symptoms and civilians with chronic fatigue have measurable postural stability problems. It has also been shown that there is a high correlation between balance ability and overall self reported health. Therefore, it is of importance to find ways of effectively quantifying and then improving balance of these individuals.



For this thesis, there were three groups of patients studied. The first group is composed of patients with no reported balanced problems (normal). The second group is composed of patients that suffer from Chronic Fatigue (CFS), which is a condition known to cause balance problems. The third group is composed of veterans with medically unexplained balance problems (veteran). To study the equilibrium score and postural stability index, data for 30 subjects (10 from each group) were randomly selected from the VA Medical Center's database. All patient data used for this thesis are from those patients who previously gave their consent for using their data in such studies. Data for each of the 30 subjects were taken from the sensory organization test, previously described in this paper.

It is believed that if the ankle stiffness is increased, the postural stability should decrease. Therefore, there should be a negative correlation between the two. In order to get a single ankle stiffness value for each subject, a composite stiffness was calculated in a manner similar to calculating the composite PSI and ES.

The average sway angle was calculated using MATLAB, by finding the mean of the theta values for all 18 trials done by each patient. This is done to indicate approximately, about which angle a subject tends to sway. It is believed that the closer the average sway angle is to the limits of stability the lower the postural stability should be. Therefore, the ES and PSI should show a negative correlation with positive average sway angles.

The SF-36 data was provided for a slightly different group of subjects. The group is still composed of 10 veteran patients, 10 normal patients and 10 CFS patients. For the Mental Component Summary (MCS) score, a score of 0 corresponds to someone with frequent psychological distress, social and role disability due to emotional problems, and health rated "poor". A score of 100 corresponds to a person with frequent positive affect, absence of psychological distress and limitations in usual social/role activities due to emotional problems, and health rated "excellent" (Ware, Kosinski, and Keller, 1994). Therefore, it is expected that as the MCS scores increase the composite score should increase.

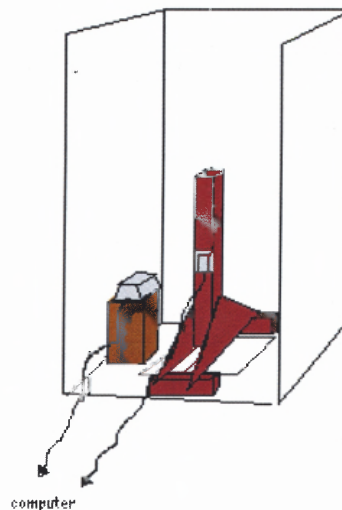
For the SF-36 Physical component summary (PCS) score, a score of 0 corresponds to a person with limitations in self-care, physical, social, and role activities, severe bodily pain, frequent tiredness, and health rated "poor". A score of 100 corresponds to a person with no physical limitations, disabilities, or decrements in well being, high energy level, and health rated "excellent". Therefore just as with the SF-36 PCS score it is expected that as the PCS increases the composite score will increase.

Another thing that was considered was the accuracy of all three scores even if the subject was not able to complete the entire 20 seconds of the trial. To do this the composite equilibrium scores and composite PSI of three subjects (one veteran, one CFS, and one normal) were computed using 5 seconds, 10 seconds, and then the complete 20 seconds of data. The composite scores for each time length were then plotted along with the standard error bars. A percent

difference was calculated, using the 20-second composite scores as the expected value.

Data was analyzed using a program written in MATLAB (see Appendix A) and Microsoft Excel. ES and PSI scores were plotted against ankle stiffness and average sway angle, to see what correlation if any, each of the scores had with these parameters. In addition to this, the composite equilibrium score and the composite postural stability index were plotted against the summary SF-36 scores. P-values were found to determine the probability of getting these correlations by chance.

#### 4.2 Accuracy of the Flock of Birds When Used With Neurocom



**Figure 4.1** Experimental setup.

In order to collect data on the sway of other joints of the body the flock of birds system is to be used. Before using this system, it is important to make sure that its recordings are precise and that the Neurocom Smart Equitest machine is not

causing interference. It is believed that the greatest cause of interference will be the force plate and motors located at the base of the machine. Therefore, preliminary tests were done to see the effects on the flock of birds as the distance from the base of the machine varies. The Flock of Birds transmitter was located 17.5 inches above the surface of the machine, and 15.5 inches to the right of the wooden stand. There are also two metal hooks, which are usually used to help secure subjects, located 44 inches above the force plate. The flock of birds device was tested under three conditions: (1) with the Neurocom Smart Equitest machine turned off, (2) with the Neurocom Smart Equitest machine turned on, and (3) with the force plate moving. The data were collected using a LabVIEW program written by Robert Demarco, a VA Medical Center employee. The program collected 3 seconds of data at each one-inch increment. The data was collected at a rate of 60Hz. The data was analyzed using a code written in MATLAB (see Appendix B). To collect the data one sensor was fixed to a wooden stand. The wooden stand contained markings that corresponded with a tape measure. The transmitter was placed on a wooden box, located within the Neurocom Smart Equitest Environment. The sensor or "bird" was moved carefully moved along the z-axis, being careful not to change the x, or y position. It is expected that by doing this, the flock of birds device will yield the same results as the tape measure in the z direction, and the x and y data points will remain the same. The data was calibrated by making sure that the first point measured at the 18.5-cm mark read 18.5 cm. This point was chosen because it

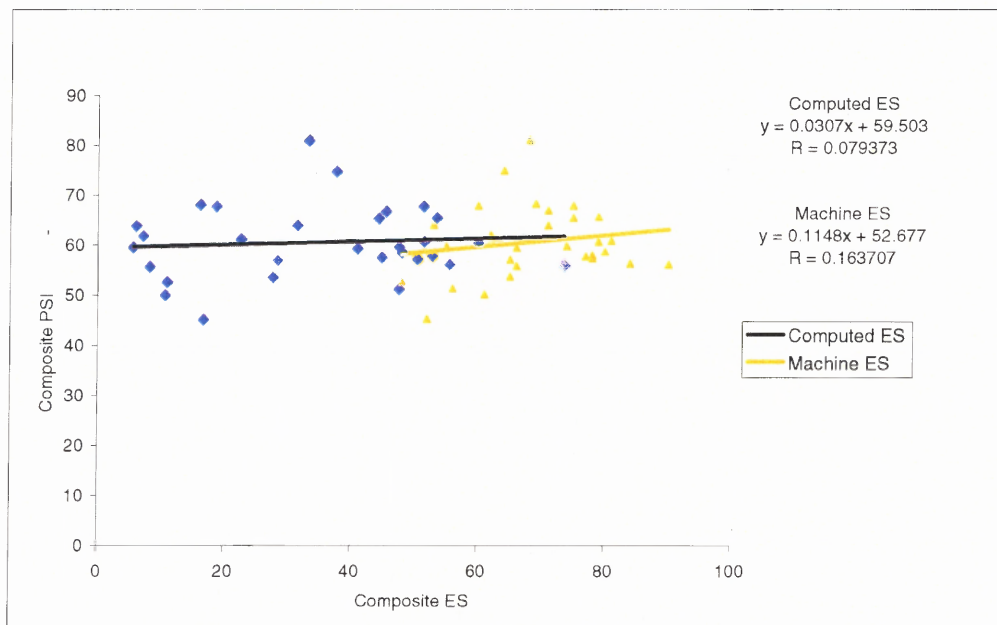
was almost in line with the vertical center of the transmitter, and because it was a reasonable distance from the force plate. The error was found by finding the distance between the anticipated and actual data points. The mean error was found for each one-inch increment, and plotted against the anticipated data point.

## CHAPTER 5

### RESULTS

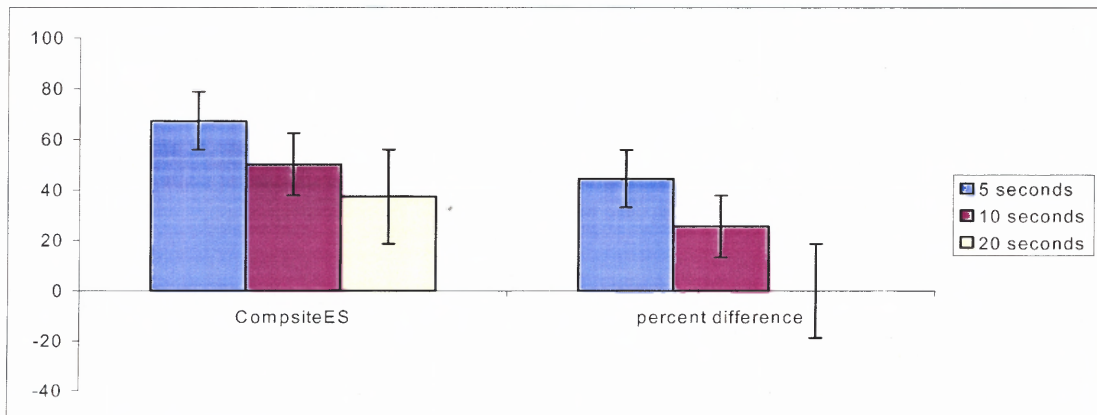
#### 5.1 Comparing PSI to ES

The following are a series of plots that compare the composite ES calculated by the Neurocom Smart Equitest machine and the composite PSI calculated using equation 1.5 from the 2-link model to the average sway angle and ankle stiffness. Before doing this, it was of interest to determine if there was any relationship between the PSI and equilibrium (computed and machine) scores. In order to determine if there is some relationship between the PSI and equilibrium scores the two were plotted against each other and the correlation coefficients were compared. As can be seen in Figure 5.1, the correlation between the composite PSI and composite equilibrium scores is very poor.

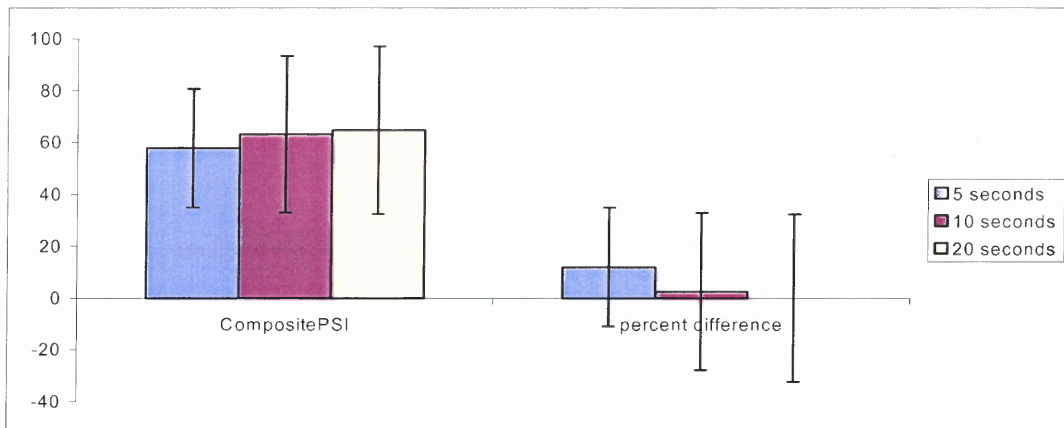


**Figure 5.1** Composite PSI score vs. composite ES score.

It was found that as the amount of recording time decreased the more the errors in the composite scores increased (Figures 5.2 & 5.3). Although both scores show some error, the PSI score appears to show less error (Figure 5.3), which could be an advantage of this score. Also, with the error bars included, the PSI data tends to overlap more, implying that there is a chance that the scores may be the same with different time intervals. On the other hand, the computed ES data tends to show little overlap (Figure 5.2), implying that there could be a difference in the scores with different time intervals.

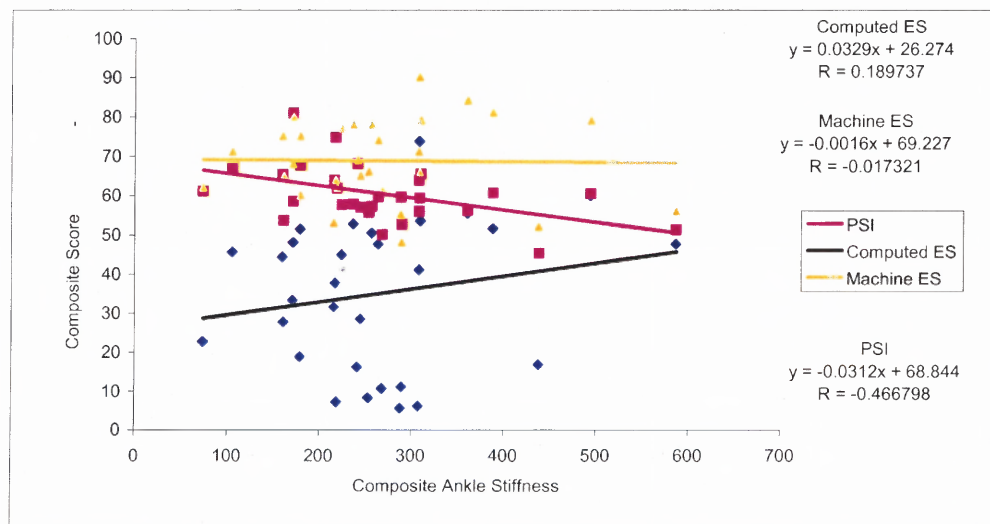


**Figure 5.2** Average composite ES with different time lengths.



**Figure 5.3** Average composite PSI with different time lengths.

### 5.1.1 Ankle Stiffness



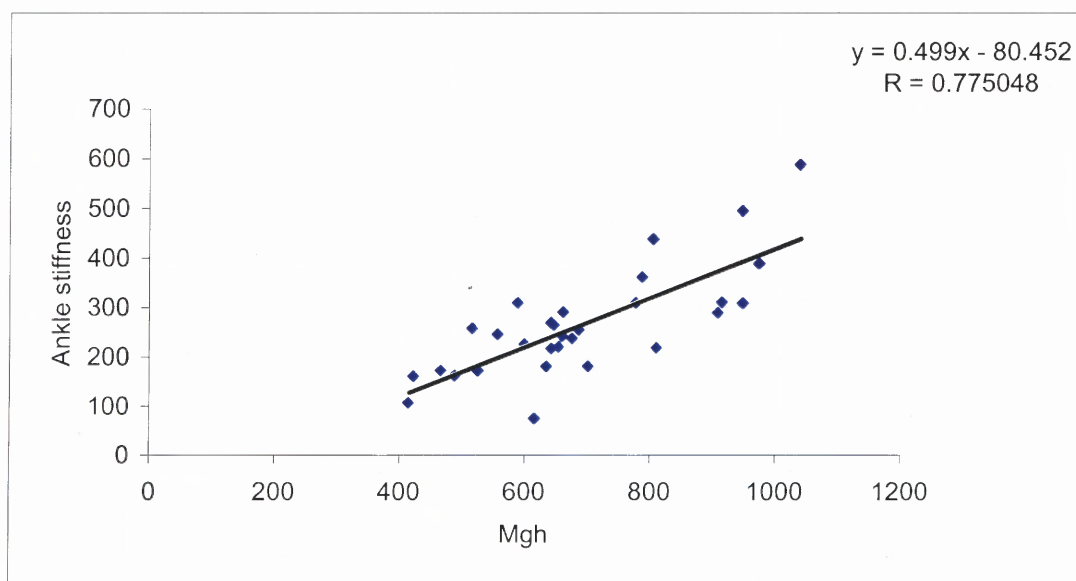
**Figure 5.4** Composite ES and PSI vs. ankle stiffness.

The composite computed ES showed a slightly positive correlation with ankle stiffness, with a correlation coefficient of .189 (Figure 5.4). The PSI and the machine ES, however showed a negative correlation with ankle stiffness, with correlation coefficients of -.467 and -.017 respectively. Here we can see that the computed ES goes against intuition and gives high scores for patients with high



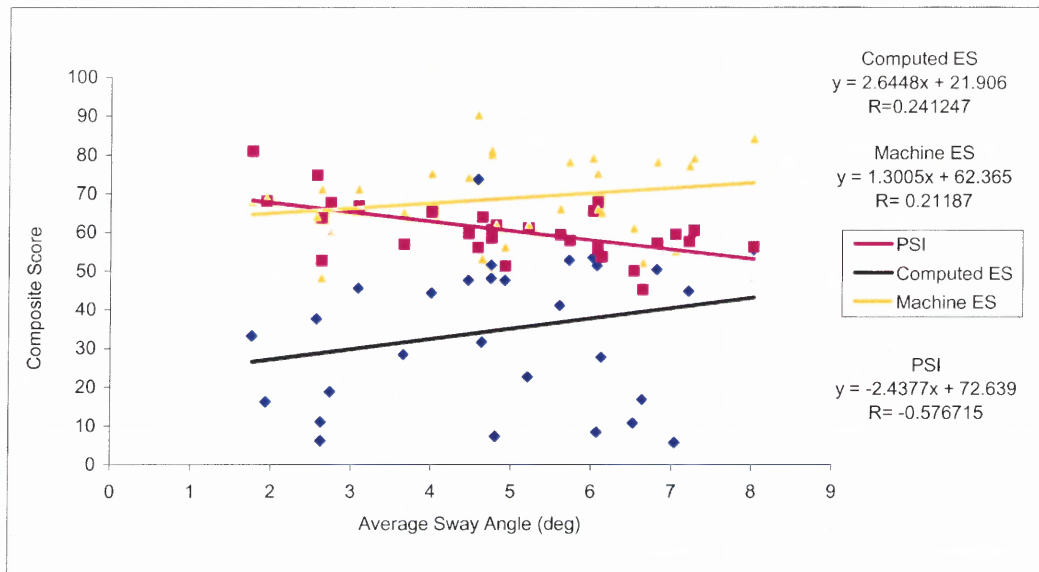
ankle stiffness and low scores for patients with little ankle stiffness. The PSI and the machine ES, on the other hand, do show what is expected. The correlation of PSI with ankle stiffness is much better than that of the machine and computed equilibrium scores.

In addition, ankle stiffness was plotted against Mgh, to see how much correlation the height and mass of the subjects has with the ankle stiffness (Figure 5.5). The results indicate a high correlation, with a correlation coefficient of .77.



**Figure 5.5** Ankle stiffness vs. Mgh.

### 5.1.2 PSI and ES Vs Average Sway Angle



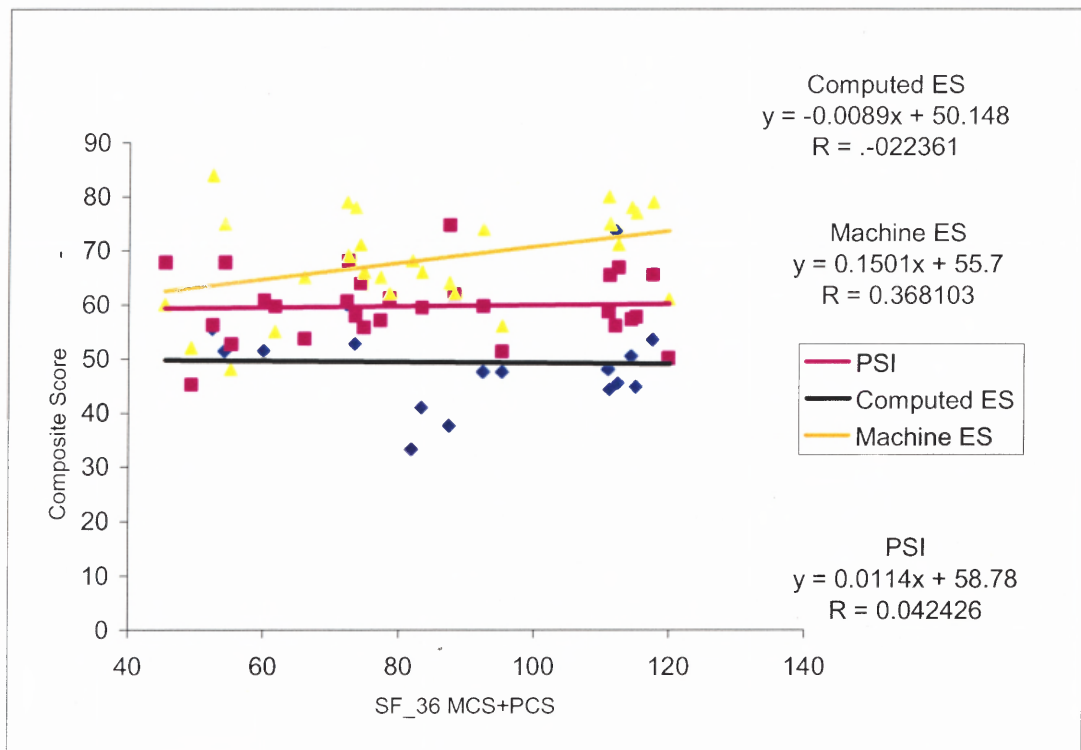
**Figure 5.6** Composite ES and PSI vs. sway angle.

Here we compare the composite computed ES, the composite machine ES and the composite PSI against the average sway angle (Figure 5.6). When this is done, we find that the PSI does in fact show a negative correlation with the average sway angle. Both the computed ES and machine composite ES, however show a positive correlation when plotted against the average sway angle.

### 5.1.3 SF-36

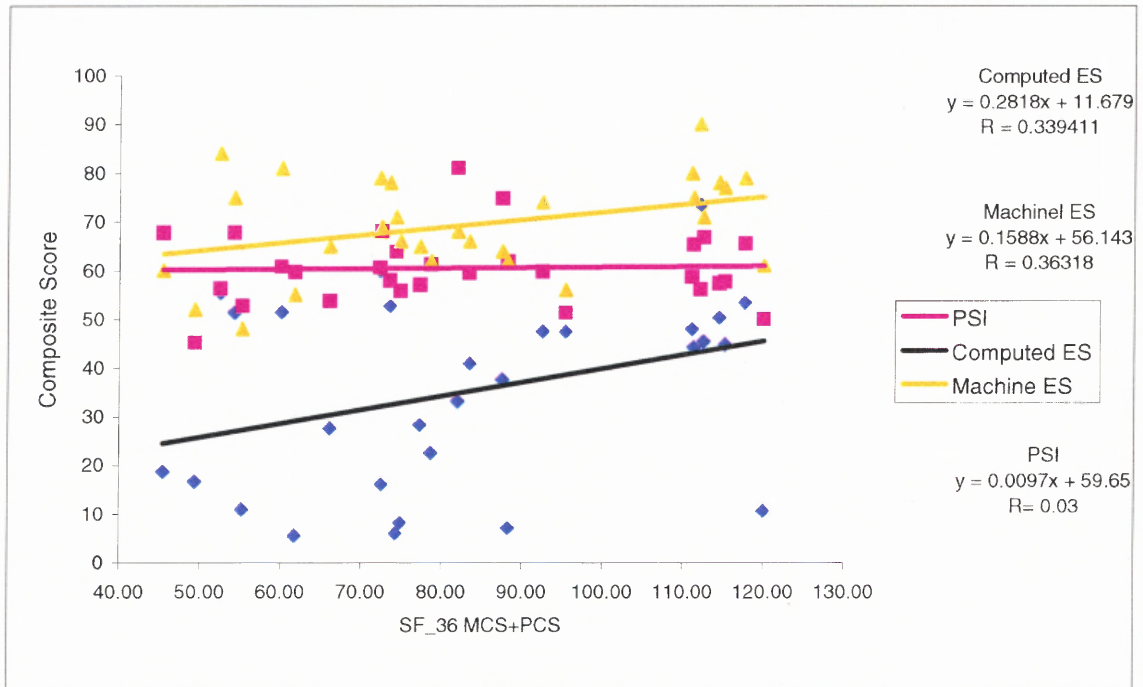
It was found (See Figure 5.7) that the composite machine ES, computed ES, and the PSI scores have a positive correlation with the sum of the PCS and MCS. After calculating the linear regression, it was found that the composite machine ES, computed ES, and the PSI scores have slopes correlation coefficients of .36,

-.022, and .04 respectively. The results show that there is possibly some correlation between the sum of the SF-36 MCS and PCS scores and the composite machine ES and computed ES.



**Figure 5.7** Composite scores vs. total SF-36 score.

When outliers were removed (Figure 5.8), it was found that the composite computed ES, machine ES, and the PSI scores have a positive (although weak) correlation with the sum of the PCS and MCS. After calculating the linear regression it was found that the composite machine ES, computed ES, and the PSI scores have correlation coefficients of .36, .34, and .03 respectively. The results show that there is possibly some correlation between the sum of the SF-36 MCS and PCS scores and the composite machine ES and computed ES.

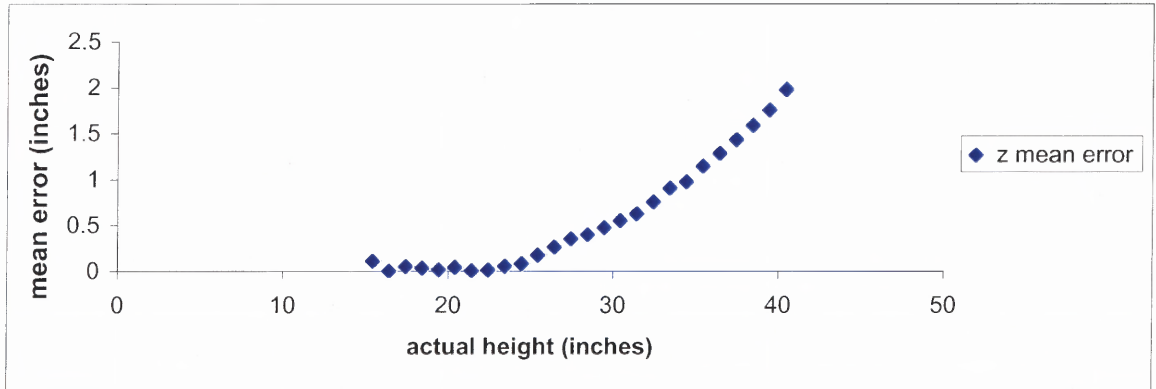


**Figure 5.8** Composite scores vs. total SF-36 score with outliers removed.

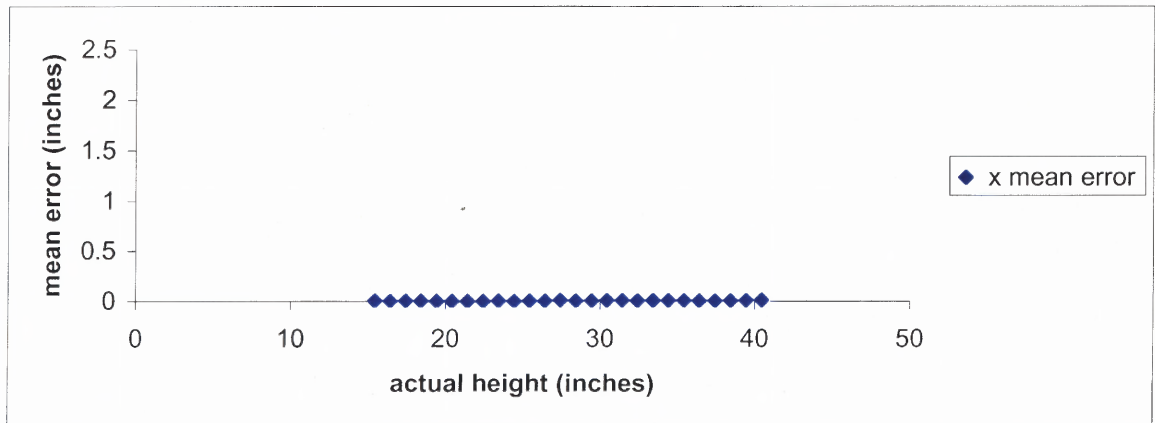
## 5.2 Accuracy of the Flock of Birds When Used With the Force Plate

The flock of birds exhibited similar results in all three environments ( see Figures 5.9,5.12, and 5.15). However, errors do vary as the z-coordinate varies. This could be either due to the distance from the transmitter or due to the metal in the force plate. However, since the error tends to increase as the sensor gets further from the force plate, it is believed that it is not the metal in the force plate causing the error, but rather the distance from the transmitter. The greatest error was found to be 2.5 inches.

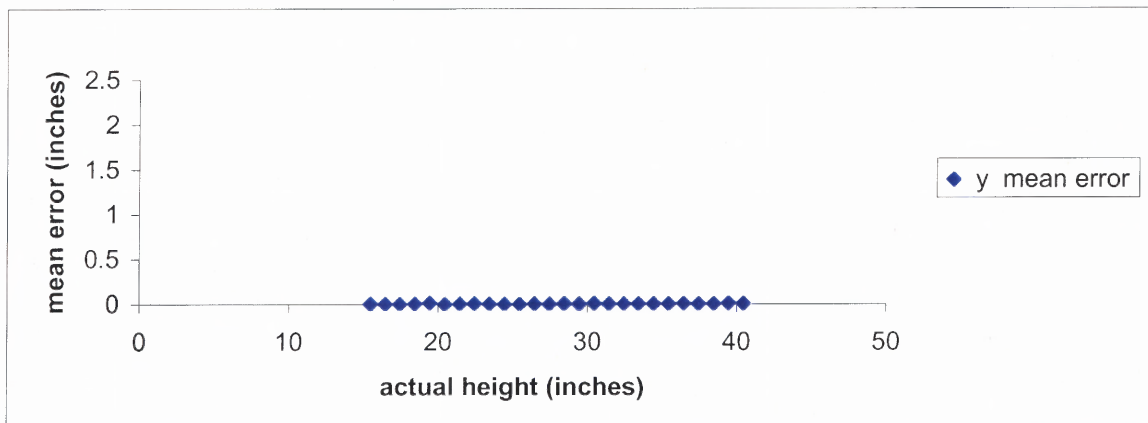
### 5.2.1 Power Off



**Figure 5.9** Mean z-axis error vs. actual height with power off.

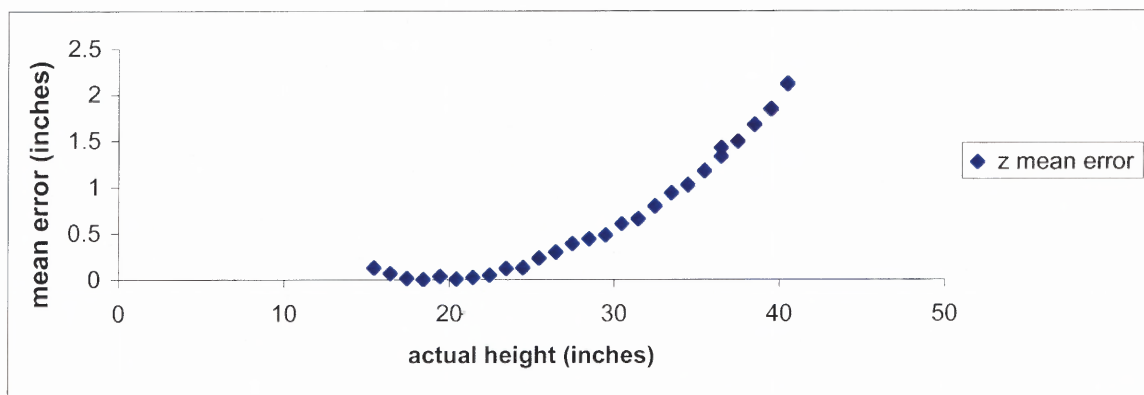


**Figure 5.10** Mean x-axis error vs. actual height with power off.

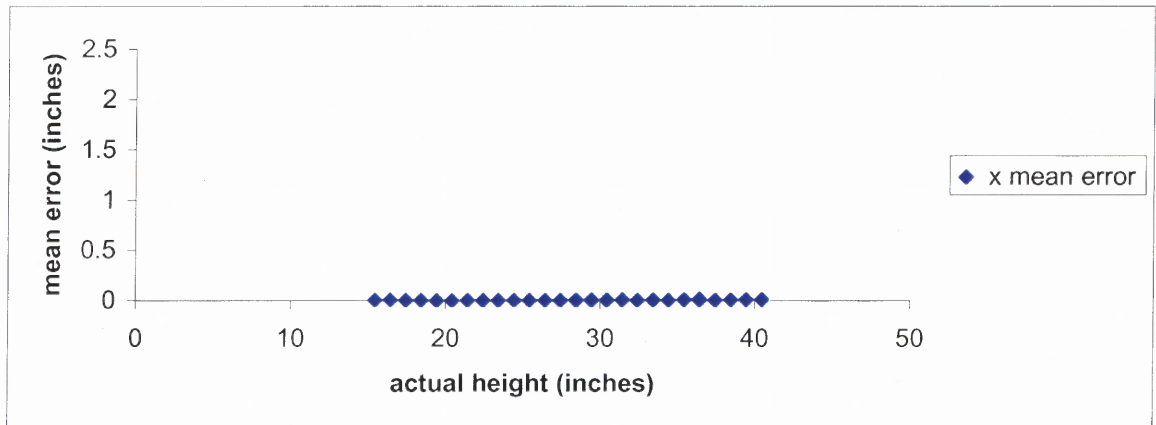


**Figure 5.11** Mean y-axis error vs. actual height with power off.

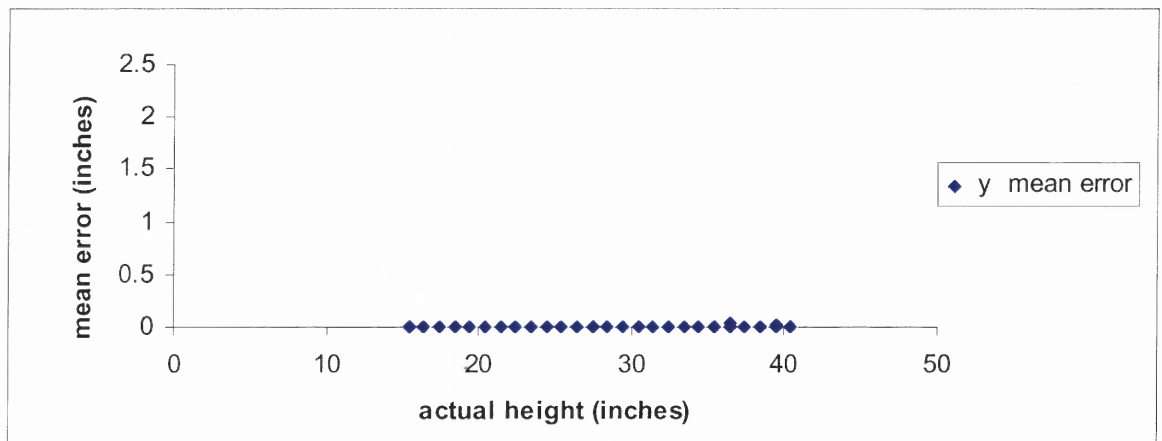
### 5.2.2 Power On



**Figure 5.12** Mean z-axis error vs. actual height with power on.



**Figure 5.13** Mean x-axis error vs. actual height with power on.



**Figure 5.14** Mean y-axis error vs. actual height with power on.

### 5.2.3 Platform Moving

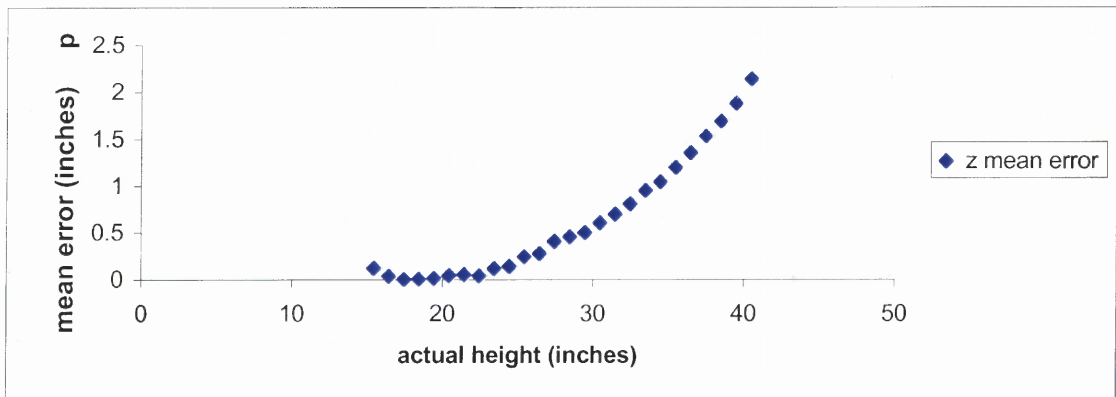


Figure 5.15 Mean z-axis error vs. actual height with moving force plate.

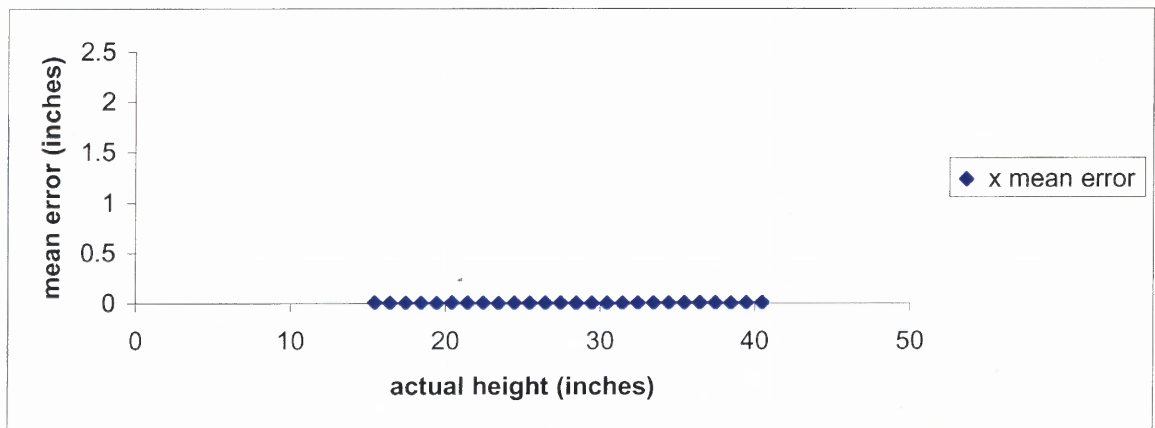
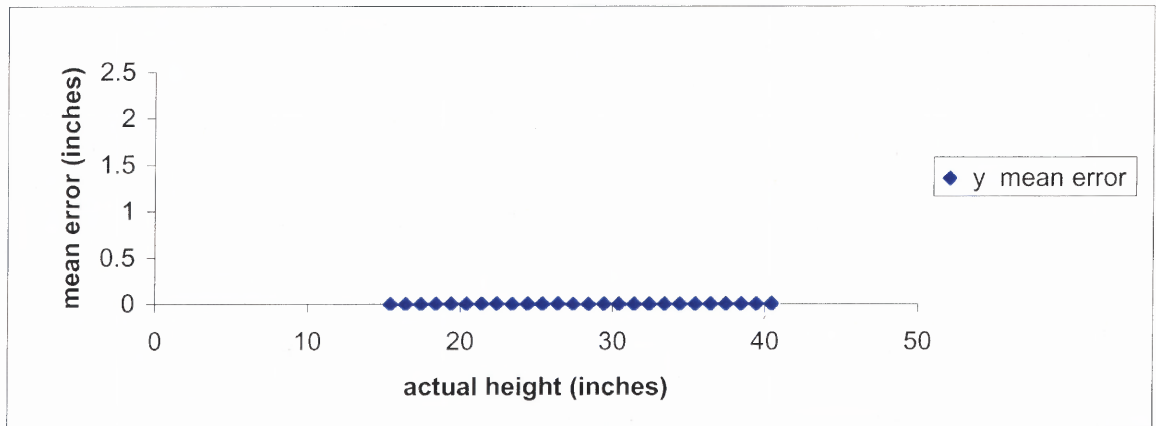


Figure 5.16 Mean x-axis error vs. actual height with moving force plate.





**Figure 5.17** Mean y-axis error vs. actual height with moving force plate.

## CHAPTER 6

### CONCLUSION

The ambiguities involved in ES are discussed, and the new measure of stability, that is PSI, is introduced. It is found that there is a high correlation between Mgh and ankle stiffness. Since ankle stiffness is a key parameter it would be advantageous to include Mgh in any formula that is used to quantify postural stability. This term is included in the formula for PSI, but is missing from the formula for ES.

It is found that the PSI does show the desired correlation with ankle stiffness and average sway angle. The regression line when PSI is plotted against the average sway angle shows a very good correlation with the data points. The correlation between the composite PSI score and the sway angle appears to be very promising, because the more a person sways the less the PSI. However, the correlation of the PSI and the equilibrium scores between all others relationships is still yet to be determined, since the regression lines for all of the other relationships have p-values greater than .05. Therefore, analysis of more subjects will be needed before making further conclusions. It is found that neither ES nor PSI has a strong correlation with the SF-36 summary scores, although ES has a better correlation than PSI. The possible reasons for weak correlation between the PSI and SF-36 summary scores could be that a person's overall mental and physical health might not be correlated to the ankle stiffness. Also, this PSI score is based only on the two-link model, which ignores hip and

knee motion. Therefore, a new formula for PSI based on the four-link model needs to be developed.

The errors found with the block of birds are less than those found with an equivalent device (Pierie, et al., 2002). The Motion Star Device used by Pierie et al. (2002) was found to yield errors as high as 150 mm, or 6 inches. With further calibration, they were able to get errors as low as 3mm or 0.8 inches. Likewise, it is believed that with further calibration (signal processing), the error in the FOB measurements can be reduced, since error in FOB measurements are smaller than those of the Motion Star device.

## **CHAPTER 7**

### **SCOPE OF FUTURE WORK**

In the future, the scores discussed can be used to study the effectiveness of different interventions. Some interventions that have been reported to be beneficiary with regard to 'balance related' tests in older community living adults. Some of these interventions are participation in programs of walking, dancing, resistance exercise, Tai Chi, flexibility, and strengthening exercises . The group at the East Orange VA Medical Center, however, is planning to concentrate on specific interventions such as (1) Balance training exercise, (2) Improvement in the design of existing braces, (3) Structural Integration, (4) Improvement in the design of shoe inserts.

In addition to using the scores to evaluate interventions, work will be done to validate mathematical models of the postural control system. A program will be developed that allows the Flock of Birds to record data while a subject is on the Neurocom Smart Equitest. This will provide the actual positional and angular data that can then be compared to values calculated using the mathematical models, for its validation.

## APPENDIX A

### PSI CODE

This is the code written to calculate the PSI.

```
%Adapted from Postural Stability Analysis - by Zhiming Ji
%This program analyzes raw encoder data from SOT
%Modified in July to calculate the PSI and to output summary data for each
group into data files.
%Modified September 18 to calculate the same es as the machine and calculate
%the variance of theta in degrees for each condition.
%modified October 10 to do the above calculations using the absolute values of
theta.
clear all;
outputfile1=input('Enter output file name:','s');
loop=1;
swayangle=zeros(2000,6);
outputfileavg=strcat(outputfile1,'avg.txt');
fidavg=fopen(outputfileavg,'a');
fprintf(fidavg,', , , , ES, , , , , , , , , SI\n');
fprintf(fidavg,'patient,ES_cond1,ES_cond2,ES_cond3,ES_cond4,ES_cond5,ES_
cond6,CompositeES,
,meanth,Variance1,Variance2,Variance3,Variance4,Variance5,Variance6');
fprintf(fidavg,',patient,SI_cond1,SI_cond2,SI_cond3,SI_cond4,SI_cond5,SI_cond
6,CompositeSI\n');

while loop~=100
patient=input('Enter patient number:(enter d if done)','s');
if patient=='100'
    inputfile=9;
else
inputfile=strcat(patient,'sot.txt');
fid=fopen(inputfile);

g=9.81;
r2d=180/pi;
%convert load cell reading to Newton with factor g/(5.12*2.2)=g/11.264
%skip first 8 lines of data
for i=1:8
    l=fgetl(fid);
end
%line 8 contains height
sss=sscanf(l,'%8c %d');
H=sss(9)/100; %from cm to m
%read another line of data
```

```

l=fgetl(fid);
%obtain data for all trials
while feof(fid)~=1 %stop read if reaching eof
  %read next 8 lines
  for i=1:8
    if feof(fid)==1, break, end
    l=fgetl(fid);
  end
  if feof(fid)==1, break, end
  %last line contains Condition number
  sss=sscanf(l,'%16c %d');
  Cond=sss(17);
  %read another line with Trial number
  l=fgetl(fid);
  sss=sscanf(l,'%12c %d');
  Trial=sss(13);
  %read another line with Sample size
  l=fgetl(fid);
  sss=sscanf(l,'%23c %d');
  Npts(Cond,Trial)=sss(24);
  if Npts(Cond,Trial) < 2000;
    fprintf('Condition %d, Trial %d lasts only %f seconds\n',Cond, Trial,
Npts(Cond,Trial)/100);
  end
  %get rid another line
  l=fgetl(fid);
  %process next Npts lines
  for i=1:Npts(Cond,Trial)
    l=fgetl(fid);
    sss=sscanf(l,'%d %d %d %d %d %d');
    lf(Cond,Trial,i)=sss(2)*g/11.264;
    rr(Cond,Trial,i)=sss(3)*g/11.264;
    sh(Cond,Trial,i)=sss(4)*g/11.264;
    lr(Cond,Trial,i)=sss(5)*g/11.264;
    rf(Cond,Trial,i)=sss(6)*g/11.264;
  end
  %get the mean weight in Kg

Wt(Cond,Trial)=mean(lf(Cond,Trial,:)+rr(Cond,Trial,:)+lr(Cond,Trial,:)+rf(Cond,Trial,:))/g;
end %while
fclose(fid);
%get the average weight from Conditions 1, 2 and 3
Wt2=mean(Wt'); %get average weight for each Condition

```

```

W=mean(Wt2(1:3));
%dimension and inertial parameters for different body parts
M1=0.09*W;
M2=0.202*W;
M3=0.678*W;
m=0.03*W;
e=0.039*H;
d=4.2*0.0254; %force sensor to pin
a=0.249*0.152*H;
l1=(0.285-0.039)*H; l2=(0.53-0.285)*H;
lc1=0.567*l1;    lc2=0.567*l2;lc3=0.175*H;
k1=0.643*l1;    k2=0.653*l2;
J1=M1*k1^2;    J2=M2*k2^2;
%calculating J3
ls=0.288*H;
l5=0.188*H;    l6=0.145*H;    l7=0.108*H;
lc5=0.564*l5; lc6=0.570*l6;    lc7=0.506*l7;

m4=0.579*W;    m5=0.054*W;    m6=0.032*W;
m7=0.013*W;
kp4=0.389*H;    kp5=0.542*l5;    kp6=0.526*l6;    kp7=0.587*l7;
l4=m4*kp4^2;    l5=m5*(kp5^2+ls*(ls-2*l5+2*lc5)); l6=m6*(kp6^2+(ls-l5)*(ls-l5-2*l6+2*lc6));
l7=m7*(kp7^2+(l5+l6-ls)*(l5+l6-ls+2*lc7));

J3=l4+l5+l6+l7;
%single joint data
M=M1+M2+M3;
h=(M1*lc1+M2*(l1+lc2)+M3*(l1+l2+lc3))/M;
l=J1+J2+J3+M2*(l1+2*lc2)*l1+M3*(l1+l2+2*lc3)*(l1+l2);
k=(l/M)^0.5;

outputfile=strcat(outputfile1,'.txt');
theta=strcat(outputfile1,'theta.txt');
fid = fopen(outputfile,'a');
fid3=fopen(theta,'a');
fprintf(fid,'patient number is %12s\n',patient);
%save subject's information to data file
fprintf(fid,'NC,NT,Npts,');
fprintf(fid,'B,D,Sl,es,es_mean,Sl_mean\n');
%work on Conditions 1 to 6
Gain=0.0; %default Gain for Conditions 1, 2 and 3
counter=14;
for i=1:Cond

```

```

for j=1:3
    if Npts(i,j)==0, break, end
        if i > 3
            Gain=1.0; %Change if not 1
        end
        ff=(lf(i,j,:)+rf(i,j,:)); %front force
        fr=(lr(i,j,:)+rr(i,j,:)); %rear force
        fh=sh(i,j,:); %horizontal force
        for n=1:Npts(i,j)
            th(n)=(M*h*((ff(n)-fr(n))*d+e*fh(n)-m*g*a)+l*fh(n))/(M^2*h^2*g-((M+m)*g-
(ff(n)+fr(n))/(1+Gain))*l);

            com(n)=h*th(n);
            temp=(g*(M+m)-(ff(n)+fr(n))-fh(n)*th(n)/(Gain+1))/(M*h);
            machinePy(n)=((ff(n)-fr(n))/(ff(n)+fr(n)))^4.2;
            machineHcog=0.5527*H;
            machineth(n)=asin(machinePy(n)./machineHcog)-2.3;
            fprintf(fid3,'%6.3f\n',th(n));
            if temp<0
                temp=0;
            end
            thd(n)=temp^0.5; %magnitude of theta dot
            Ml(n)=(lf(i,j,n)-lr(i,j,n))*d; %moment from left
            Mr(n)=(rf(i,j,n)-rr(i,j,n))*d; %moment from right
            Mh(n)=fh(n)*e; %moment% from horizontal friction
            tau(n)=(ff(n)-fr(n))*d+Mh(n)-m*g*a;
            Wr(n)=(rf(i,j,n)+rr(i,j,n))*100/(ff(n)+fr(n)); %weight percentage on right foot
        end
        %linear regression tau=aa(1)*theta+aa(2)
        aa=polyfit(th,tau,1);
        ymean=mean(tau);
        for n=1:Npts(i,j)
            e1(n)=(ymean-aa(1)*th(n)-aa(2))^2;
            e2(n)=(ymean-tau(n))^2;
        end
        R2=sum(e1)/sum(e2); %R^2 for single-variable regression
        dy=tau-polyval(aa,th); %deviation of moment about the regression
        y_e=M*g*h*th-tau; %effective moment
        dt_min=min(y_e);
        dt_max=max(y_e);
        %new stuff for stability index
        D=sum(abs(tau));
        B=sum(abs(M*g*h*th));

```



```

Slcheck=(B/D)*100;
if Slcheck <=100
    SI=Slcheck;
else SI=(10000/Slcheck);
end

%min and max of sway angle and ankle moment
tau_min=min(tau);
tau_max=max(tau);
th_min=min(th);
th_max=max(th);
machineth_min=min(machineth);
machineth_max=max(machineth);
machinedelta_th=machineth_max-machineth_min;
delta_tau=tau_max-tau_min;
delta_th=th_max-th_min;
%create the line of the regression of 200 pts
inc=delta_th/200;
for n=1:200
    t2(n)=th_min+inc*(n-1);
    ybar(n)=aa(1)*t2(n)+aa(2);
end
%Equilibrium Score
es=(1-machinedelta_th/12.5)*100;
Wr_mean=mean(Wr);
Wr_min=min(Wr);
Wr_max=max(Wr);
Ml_mean=mean(Ml);
Ml_min=min(Ml);
Ml_max=max(Ml);
Mr_mean=mean(Mr);
Mr_min=min(Mr);
Mr_max=max(Mr);
Mh_mean=mean(Mh);
Mh_min=min(Mh);
Mh_max=max(Mh);

%convert angle to degree
th_min=min(th)*r2d;
th_max=max(th)*r2d;
delta_th=delta_th*r2d;

cond2(i,j)=i; trial2(i,j)=j; B2(i,j)=B; D2(i,j)=D; SI2(i,j)=SI; es2(i,j)=es;
ES_mean=mean(es2,2)*[0,0,1];

```

```

SI_mean=mean(SI2,2)*[0,0,1];

%check to make sure sufficient number of pts 2000
%composite score pt check.

if Npts(i,j)==2000
    escheck(i,j)=es2(i,j);
    sicheck(i,j)=SI2(i,j);
else
    escheck(i,j)=0;
    sicheck(i,j)=0;
    counter=counter-1;
end

fprintf(fid,'%d,%d,%d',i,j,Npts(i,j));

fprintf(fid,'%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f\n',B2(i,j),D2(i,j),SI2(i,j),es2(i,j),E
S_mean(i,j),SI_mean(i,j));

    Loc=round(Npts(i,j)/4);

    t=0:0.01:(Npts(i,j)-1)/100;    c=[th';zeros(2000-Npts(i,j),1)];
        swayangle(:,(i-1)*3+j)=c;
    dswayangle=swayangle*r2d;
    variance=std(abs(dswayangle)).^2;
    testmean=mean(mean(abs(swayangle)));
    boundary=size(find(swayangle>=.15))+size(find(swayangle<-.01));
    clear th com thd tau Wr Ml Mr Mh;
    %because their sizes may change in the following Trials
end
end
%calculating variance
variance1=(variance(1)+variance(2)+variance(3))/3;
variance2=(variance(4)+variance(5)+variance(6))/3;
variance3=(variance(7)+variance(8)+variance(9))/3;
variance4=(variance(10)+variance(11)+variance(12))/3;
variance5=(variance(13)+variance(14)+variance(15))/3;
variance6=(variance(16)+variance(17)+variance(18))/3;

%calculating composite scores
compes=(ES_mean(1,3)+ES_mean(2,3)+sum(escheck(3,:))+sum(escheck(4,:))+
sum(escheck(5,:))+sum(escheck(6,:)))/counter;

```

```

compsi=(SI_mean(1,3)+SI_mean(2,3)+sum(sicheck(3,:))+sum(sicheck(4,:))+
sum(sicheck(5,:))+sum(sicheck(6,:)))/counter;
fprintf(fid,'compes,%6.3f\n',compes);
fprintf(fid,'compsi,%6.3f\n',compsi);

```

```

fprintf(fidavg,'%12s,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f',patient,ES_me
an(1,3),ES_mean(2,3),ES_mean(3,3),ES_mean(4,3),ES_mean(5,3),ES_mean(6,
3),compes);
fprintf(fidavg,'%12s,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f',patient,t
estmean,variance1,variance2,variance3,variance4,variance5,variance6);
fprintf(fidavg,'%12s,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f\n',patient,SI_me
an(1,3),SI_mean(2,3),SI_mean(3,3),SI_mean(4,3),SI_mean(5,3),SI_mean(6,3),c
ompsi);

```

```

end
loop=patient+0;
end
fclose(fid);
fclose(fidavg);
fclose(fid3);
fprintf('done')

```

## APPENDIX B

### FLOCK OF BIRDS CODE

Code written to analyze the flock of birds data.

%Before using this program make sure to insert 5 lines before the first line of the data file.

```
clear all
```

```
outputfile1=input('Enter output file name:','s');
```

```
fidout=fopen(outputfile1,'a');
```

```
filename=input('Input the file name:','s');
```

```
fid=fopen(strcat('C:\Documents and Settings\Owner\My  
Documents\Desktop\thesis\flockdata\',filename));
```

```
fprintf(fidout,'actual,x,y,z,x std error, x mean error,y std error, y mean std, z std  
error, z mean std\n');
```

```
k=1;
```

```
in2cm=1;
```

```
for i=1:10
```

```
    l=fgetl(fid);
```

```
end
```

```
    if l==-1 break,end
```

```
    actualin=sscanf(l,'%2f');
```

```
    actualcm=actualin.*in2cm;
```

```
if feof(fid)==1, break, end
```

```
%grab each of the data points collected
```

```
for i=1:180
```

```
    l=fgetl(fid);
```

```
    getdata=sscanf(l,'%f %f %f %f %f %f',10);
```

```
    %calibration term for flock of birds
```

```
    zcalibrate(i)=sum(actualcm)-getdata(3);
```

```
    observed(i,1)=getdata(1);
```

```
    observed(i,2)=getdata(2);
```

```
    observed(i,3)=zcalibrate(1)+getdata(3);
```

```
    error(i,1)=abs(observed(i,1)-observed(1,1));
```

```
    error(i,2)=abs(observed(i,2)-observed(1,2));
```

```
    error(i,3)=abs(observed(i,3)-sum(actualcm));
```

```
end
```

```
STD=std(error);
```

```
average=mean(error);
```

```

output(k,1)=sum(actualcm);
output(k,2)=mean(observed(:,1));
output(k,3)=mean(observed(:,2));
output(k,4)=mean(observed(:,3));
output(k,5)=STD(1);
output(k,6)=average(1);
output(k,7)=STD(2);
output(k,8)=average(2);
output(k,9)=STD(3);
output(k,10)=average(3);

```

```

fprintf(fidout,'%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f\n',o
utput(k,1),output(k,2),output(k,3),output(k,4),output(k,5),output(k,6),output(k,7),ou
tput(k,8),output(k,9),output(k,10));
k=k+1;
l=fgetl(fid);

```

```

while feof(fid)~=1

```

```

if feof(fid)==1, break, end

```

```

%Go eight lines to grab the actual(theoretical) data point

```

```

for i=1:10

```

```

    l=fgetl(fid);

```

```

end

```

```

    if l==-1 break,end

```

```

    actualin=sscanf(l,'%2f');

```

```

    actualcm=actualin.*in2cm;

```

```

if feof(fid)==1, break, end

```

```

%grab each of the data points collected

```

```

for i=1:180

```

```

    l=fgetl(fid);

```

```

    getdata=sscanf(l,'%f %f %f %f %f %f',10);

```

```

    observed(i,1)=getdata(1);

```

```

    observed(i,2)=getdata(2);

```

```

    observed(i,3)=zcalibrate(1)+getdata(3);

```

```

    error(i,1)=abs(observed(i,1)-observed(1,1));

```

```

    error(i,2)=abs(observed(i,2)-observed(1,2));

```

```

    error(i,3)=abs(observed(i,3)-sum(actualcm));

```

```

end
STD=std(error);
average=mean(error);
output(k,1)=sum(actualcm);
output(k,2)=mean(observed(:,1));
output(k,3)=mean(observed(:,2));
output(k,4)=mean(observed(:,3));
output(k,5)=STD(1);
output(k,6)=average(1);
output(k,7)=STD(2);
output(k,8)=average(2);
output(k,9)=STD(3);
output(k,10)=average(3);

fprintf(fidout,'%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f\n',o
utput(k,1),output(k,2),output(k,3),output(k,4),output(k,5),output(k,6),output(k,7),ou
tput(k,8),output(k,9),output(k,10));

k=k+1;
l=fgetl(fid);
end
subplot(2,2,1); plot(output(:,1),output(:,4)); title('z axis');
subplot(2,2,2); plot(output(:,1),output(:,5)); title('SEM');

subplot(2,2,3); plot(output(:,1),output(:,2)); title('x axis');
subplot(2,2,4); plot(output(:,1),output(:,3)); title('y axis');

fclose(fid);
fclose(fidout);

```

## APPENDIX C

### ANKLE STIFFNESS ALGORITHM

This algorithm calculates the ankle stiffness for each trial and finds the mean stiffness for each condition as well as the composite stiffness.

```
%@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
%calculating ankle stiffness
for i=1:18
fit=polyfit(swayangle(:,i),torque(:,i),1);
anklestiffness(i)=fit(1);
end
%@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@

% calculating composite scores
compes=(ES_mean(1,3)+ES_mean(2,3)+sum(escheck(3,:))+sum(escheck(4,:))+
sum(escheck(5,:))+sum(escheck(6,:)))/counter;
compsi=(SI_mean(1,3)+SI_mean(2,3)+sum(sicheck(3,:))+sum(sicheck(4,:))+
sum(sicheck(5,:))+sum(sicheck(6,:)))/counter;

stiffness1=mean([anklestiffness(1),anklestiffness(2),anklestiffness(3)]);
stiffness2=mean([anklestiffness(4),anklestiffness(5),anklestiffness(6)]);
stiffness1a=mean(abs([anklestiffness(1),anklestiffness(2),anklestiffness(3)]));
stiffness2a=mean(abs([anklestiffness(4),anklestiffness(5),anklestiffness(6)]));

stiffnessrest=anklestiffness;
%creates a matrix with only the last 12 values

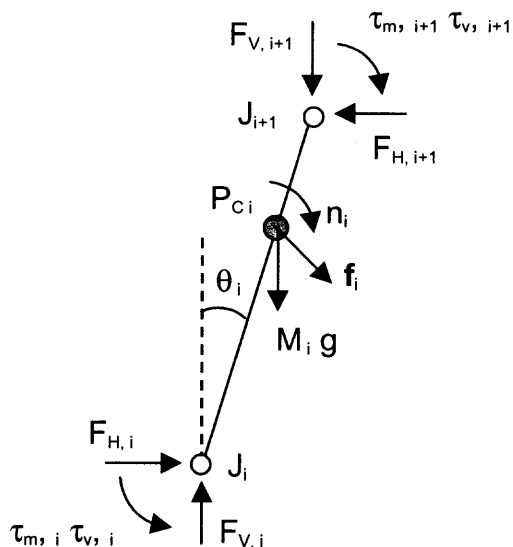
for i=1:6
    %erases the first 6 values in the matrix
    stiffnessrest(i)=[];
end

compstiffness=(stiffness1+stiffness2+sum(stiffnessrest))/14;
compstiffness2=(stiffness1a+stiffness2a+sum(abs(stiffnessrest)))/14;
```

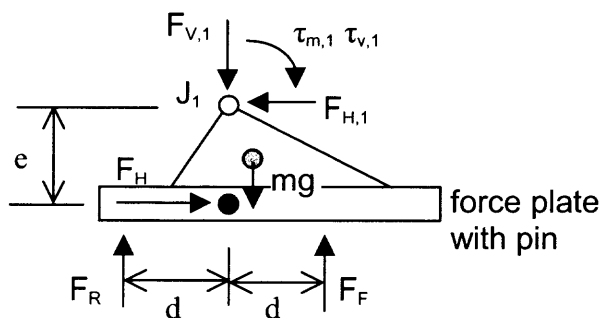
## APPENDIX D

### FOUR-LINK MODEL

These are the equations of the 4-link model discussed earlier.



**Figure D.1.** Free body diagram of 4-Link model.



**Figure D.2** Free body diagram of feet.

**Nomenclature:**

$J_i$ : lower joint of link  $i$ , (ankle joint  $J_1$ , knee joint  $J_2$ , and hip joint  $J_3$ )

$M_i$ : mass of link  $i$

$m$ : total mass of the feet and the force plate



$l_i$ : length of link  $i$

$l_{ci}$ : distance from joint  $J_i$  to center of mass  $P_{ci}$  of link  $i$

$F_{H,i}, F_{H,i+1}$ : horizontal force acting on link  $i$  at joints  $J_i$  and  $J_{i+1}$  respectively

$F_{V,i}, F_{V,i+1}$ : vertical force acting on link  $i$  at joints  $J_i$  and  $J_{i+1}$  respectively

$\tau_{m,i}$ : moment acting on link  $i$  by muscles acting at joint  $J_i$

$\tau_{v,i}$ : viscous friction moment acting on link  $i$  by muscle acting at joint  $J_i$

$\mathbf{f}_i, n_i$ : inertial force and moment of link  $i$

$F_F, F_R$ : vertical ground reaction forces measured with front and rear transducers

$F_H$ : horizontal ground reaction forces measured with horizontal transducer

$d$ : horizontal distance between the vertical transducers and the pin axis of the force plate

$e$ : vertical distance between the ankle joint and horizontal transducer of the force plate

$c$ : horizontal distance between the center of mass  $m$  and the vertical line through ankle

The acceleration at the center of mass of each link can be expressed as

$$\begin{aligned}\ddot{x}_{ci} &= \sum_{k=1}^{i-1} l_k (\cos\theta_k \ddot{\theta}_k - \sin\theta_k \dot{\theta}_k^2) + l_{ci} (\cos\theta_i \ddot{\theta}_i - \sin\theta_i \dot{\theta}_i^2) \\ \ddot{y}_{ci} &= -\sum_{k=1}^{i-1} l_k (\sin\theta_k \ddot{\theta}_k + \cos\theta_k \dot{\theta}_k^2) + l_{ci} (\sin\theta_i \ddot{\theta}_i + \cos\theta_i \dot{\theta}_i^2)\end{aligned}\quad (D.1)$$

Thus, the inertial force and moment of link  $i$  can be expressed as

$$\mathbf{f}_i = M_i \begin{bmatrix} \ddot{x}_{c,i} \\ \ddot{y}_{c,i} \end{bmatrix}, \quad n_i = I_{ci} \ddot{\theta}_i \quad (D.2)$$

Newton-Euler equations for link  $i$  can now be written as

$$F_{H,i} - F_{H,i+1} = M_i \ddot{x}_{c,i}$$

$$F_{V,i} - F_{V,i+1} = M_i (g + \ddot{y}_{c,i})$$

$$\tau_{m,i+1} - \tau_{m,i} + \tau_{v,i+1} - \tau_{v,i} + F_{V,i+1}(l_i - l_{ci}) \sin\theta_i - F_{H,i+1}(l_i - l_{ci}) \cos\theta_i + F_{V,i} l_{ci} \sin\theta_i - F_{H,i} l_{ci} \cos\theta_i = I_{ci} \ddot{\theta}_i \quad (D.3)$$

with

$$F_{H,4} = F_{V,4} = \tau_{m,4} = \tau_{v,4} = 0$$

Newton-Euler equation for feet with force plate can now be written as

$$F_H - F_{H,1} = 0$$

$$F_F + F_R - F_{V,1} = mg \quad (D.4)$$

$$\tau_{m,1} + \tau_{v,1} - (F_F - F_R)d - F_H e + mgc = 0$$

After eliminating all the internal forces and moments  $F_{H,i}, F_{V,i}, \tau_{m,i}$ , and  $\tau_{v,i}$  ( $i = 1, \dots, 3$ ), we have the following three equations:

$$[M_1 l_{c1} + (M_2 + M_3) l_1] \ddot{\theta}_1 \cos \theta_1 + (M_2 l_{c2} + M_3 l_2) \ddot{\theta}_2 \cos \theta_2 + M_3 l_{c3} \ddot{\theta}_3 \cos \theta_3 - [M_1 l_{c1} + (M_2 + M_3) l_1] \dot{\theta}_1^2 \sin \theta_1 - (M_2 l_{c2} + M_3 l_2) \dot{\theta}_2^2 \sin \theta_2 - M_3 l_{c3} \dot{\theta}_3^2 \sin \theta_3 = F_H \quad (D.5)$$

$$[M_1 l_{c1} + (M_2 + M_3) l_1] \ddot{\theta}_1 \sin \theta_1 + (M_2 l_{c2} + M_3 l_2) \ddot{\theta}_2 \sin \theta_2 + M_3 l_{c3} \ddot{\theta}_3 \sin \theta_3 + [M_1 l_{c1} + (M_2 + M_3) l_1] \dot{\theta}_1^2 \cos \theta_1 + (M_2 l_{c2} + M_3 l_2) \dot{\theta}_2^2 \cos \theta_2 + M_3 l_{c3} \dot{\theta}_3^2 \cos \theta_3 = (M_1 + M_2 + M_3 + m)g - (F_F + F_R) \quad (D.6)$$

$$\begin{aligned} & \left[ l_1 + (M_2 + M_3) l_1^2 + (M_2 l_{c2} + M_3 l_2) l_1 \cos \theta_2 - \theta_1 + M_3 l_1 l_{c3} \cos \theta_3 - \theta_1 \right] \ddot{\theta}_1 + \\ & \left[ l_2 + M_3 l_2^2 + (M_2 l_{c2} + M_3 l_2) l_1 \cos \theta_2 - \theta_1 + M_3 l_2 l_{c3} \cos \theta_3 - \theta_1 \right] \ddot{\theta}_2 + \\ & \left[ l_3 + M_3 l_1 l_{c3} \cos \theta_3 - \theta_1 + M_3 l_2 l_{c3} \cos \theta_3 - \theta_2 \right] \ddot{\theta}_3 \\ & - (M_2 l_{c2} + M_3 l_2) l_1 (\dot{\theta}_2^2 - \dot{\theta}_1^2) \sin \theta_2 - \theta_1 - M_3 l_1 l_{c3} (\dot{\theta}_3^2 - \dot{\theta}_1^2) \sin \theta_3 - \theta_1 - M_3 l_2 l_{c3} (\dot{\theta}_3^2 - \dot{\theta}_2^2) \sin \theta_3 - \theta_2 \\ & = [(M_1 l_{c1} + M_2 l_1 + M_3 l_1) \sin \theta_1 + (M_2 l_{c2} + M_3 l_2) \sin \theta_2 + M_3 l_{c3} \sin \theta_3] g - (F_F - F_R) d - F_H e + m g c \end{aligned} \quad (D.7)$$

where  $I_i = I_{ci} + M_i l_{ci}^2$  is the moment of inertia of link  $i$  about  $J_i$  joint axis.

Equations (5) –(7) are solved for sway angles at the joints after getting the initial conditions from Flock of Birds and the raw data from Equitest device. Then the last part of the equations (3) and (4) are used to evaluate the torques and therefore the muscle stiffness (which is the derivative of the torque with respect sway angle) at the joints. For the two-link model, the equations for the sway angle and the torque are given below:

$$\theta = \frac{Mh[(F_F - F_R)d + F_H e - mga] + I \cdot F_H}{M^2 gh^2 - I \left[ (M + m)g - \frac{F_F + F_R}{k + 1} \right]} \quad (D.8)$$

and

$$\tau = (F_F - F_R)d + F_H e - mga \cos \frac{k\theta}{k + 1} \quad (D.9)$$

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