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Postural Sway, EEG and EMG Analysis of Hip and Ankle Muscles during Eight Balance Training Tasks

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LOMA LINDA UNIVERSITY
School of Allied Health Professions
in conjunction with the
Faculty of Graduate Studies

Postural Sway, EEG and EMG Analysis of Hip and Ankle Muscles during Eight Balance Training Tasks

by

Yuen Yi Florence Tse

A Dissertation submitted in partial satisfaction of
the requirements for the degree
Doctor of Science in Physical Therapy

June 2012

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Each person whose signature appears below certifies that this dissertation in his/her opinion is adequate, in scope and quality, as a dissertation for the degree Doctor of Science.

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ABBREVIATIONS

ANOVA	Analysis of Variance
BOS	Base of Support
CNS	Central Nervous System
CV	Coefficient of Variation
Cz	Electroencephalography Channel at the Midline of the Central area
EMG	Electromyography
EEG	Electroencephalography
FAEO-FIRM	Feet Apart with Eyes Open on Firm surface
FAEO-FOAM	Feet Apart with Eyes Open on Foam surface
FAEC-FIRM	Feet Apart with Eyes Closed on Firm surface
FAEC-FOAM	Feet apart with Eyes Closed on Foam surface
fMRI	Functional Magnetic Resonance Imaging
Fz	Electroencephalography Channel at the Midline of the Frontal Area
GAST	Medial Gastrocnemius
GMAX	Gluteal Maximus
GMED	Gluteal Medius
Hz	Hertz
MVC	Maximum Voluntary Isometric Contraction
PET	Positron Emission Tomography
POz	Electroencephalography Channel at the Midline of the Parietal Area

PSD	Power Spectral Densities
SD	Standard Deviation
SEM	Standard Error of Mean
SURFACE	Surface Compliance
TA	Tibialis Anterior
TEMG	Average EMG activity of all the Muscles
TEMG work	Total Muscle Work of all the Muscles
TEO-FIRM	Tandem Standing with Eyes Open on Firm Surface
TEO-FOAM	Tandem Standing with Eyes Open on Foam Surface
TEC-FIRM	Tandem Standing with Eyes Closed on Firm Surface
TEC-FOAM	Tandem Standing with Eyes Closed on Foam Surface

ABSTRACT OF THE DISSERTATION

Postural Sway, EEG and EMG Analysis of Hip and Ankle Muscles
during Eight Balance Training Tasks

by

Yuen Yi Florence Tse

Doctor of Science, Graduate Program in Physical Therapy
Loma Linda University, June 2012
Dr. Jerrold S. Petrofsky, Chairperson

The purpose of this study was to examine postural sway, cortical response and muscle activation of the hip and ankle muscles during eight balance tasks routinely used in sensorimotor training. This was a single group repeated measure study. The postural sway; the power of alpha, beta and sigma wave bands; and the EMG activity of gluteal maximus, gluteal medius, tibialis anterior and medial gastrocnemius were measured in 17 subjects during eight balance tasks with eyes open or closed, feet in tandem or apart and on foam or a firm surface.

The results of this study showed that postural sway, EEG power of the beta and sigma wave bands, and EMG activity of the hip and ankle muscles were significantly higher due to the alteration of sensory information in the eight common balance tasks when compared to the control task. The postural sway was affected by the extent of sensory information available for postural control. The recruitment of specific muscles was affected by the context of the tasks rather than the number of sensory factors altered. EEG power of beta and sigma wave bands showed significant increases at the central and parietal area of the brain relative to the control tasks when eyes were open in the tasks. The cortical involvement decreased as the task became more difficult with vision and

somatosensory information altered. When the balance task became more challenging with vision, base of support and surface compliance altered, the cortical activity increased significantly again.

The postural sway and cortical activity were affected by the amount of sensory information available for postural control. The recruitment of specific muscles was affected by the context of the tasks rather than the numbers of sensory factor altered. Our results suggest that balance training should start with alteration of one sensory factor by first altering the somatosensory input (base of support then the surface compliance), and followed by excluding the visual input. The balance training should then be progressed by altering two then three sensory factors. A balance program should include exercises to strengthen hip and ankle muscles in order to facilitate the postural control in static balance tasks.

CHAPTER ONE

INTRODUCTION

Significance of Balance Training

The serious health, social and economic consequences of accidental falls are well documented (WISQARS, 2010, WISQARS, 2009, Stevens et al., 2006, Cost of 2006). The deterioration of balance increases the risk of falling and ultimately leads to an increase in health care costs and even mortality (Lord et al., 1991, Campbell et al., 1989). Balance training has been known to restore balance control and to reduce the risk of falling (Madureira et al., 2007, Gillespie et al., 2009a, Sherrington et al., 2008). It was presumed that balance exercises were only beneficial to the elderly population; however, it has been shown to be advantageous to a variety of populations. Balance training has been shown to improve balance in people with Parkinson's disease (Hirsch et al., 2003), stroke (Yavuzer et al., 2006) or osteoarthritis (Duman et al., 2011, Messier et al., 2000). It has been shown to improve strength (Heitkamp et al., 2001, Bruhn et al., 2006), neuromuscular activation (Gruber and Gollhofer, 2004), jumping ability (Bruhn et al., 2004) and vertical jump performance (Kean et al., 2006, Myer et al., 2006) in young adults. In addition, balance training has been shown to be effective in preventing sport injury (Emery et al., 2007, McGuine and Keene, 2006, Myklebust et al., 2007, Verhagen et al., 2004).

Complexity of Balance Control

Balance control is a complex process. It is no longer considered a summation of reflexes based on sensory input. The central nervous system has to organize and process the sensory information from visual, somatosensory and vestibular systems, to generate appropriate motor responses (Peterka, 2002, Horak and Shupert, 2000).

Cortical Response to Balance Control

Cortical control has been found to be involved in the postural tasks such as walking, stepping and disturbed walking (Jacobs and Horak, 2007, Nielsen, 2003, Christensen et al., 2001, Schubert et al., 1999). Studies have shown that central processing plays an important role in modifying postural response (Horak and Nashner, 1986, Diener et al., 1988). Cortical activity at the motor cortex has been displayed preceding the onset of postural adjustment (Saitou et al., 1996). Studies have shown the presence of anticipatory cortical response prior to a perturbation (Jacobs et al., 2008) and perturbation-evoked cortical activity after a perturbation (Quant et al., 2004, Adkin et al., 2006). These studies support the notion suggested by Slobounov and colleagues that postural adjustment is not just an automatic muscle response to perturbation but a cortically intended movement (Slobounov et al., 2005).

Sensory Influences on Balance Control

The complex sensory environment has been shown to affect postural sway (Kavounoudias et al., 1999, Day et al., 1997, Jeka et al., 1997). Alteration of the visual or vestibular input to balance has exhibited its effect on the postural sway (Peterka, 2002, Day et al., 1997, Anand et al., 2003, Liaw et al., 2009). Diminished somatosensory information has shown to decrease postural stability (Shaffer and Harrison, 2007). To maintain balance, the central nervous system needs to re-weight the relative dependence on each of the senses (Peterka, 2002). Therefore, it is important to modify the sensory environment to facilitate the sensorimotor integration in a balance-training program.

Purpose of the Study

Balance training is greatly diverse, even Tai Chi is considered to be useful for balance training (Gillespie et al., 2009a, Li et al., 2005, Wolf et al., 1997, Liu and Frank, 2010, Huang et al., 2010, Li et al., 2004). However, the exercises and tasks used in various balance programs are not standardized, The general guideline for balance exercises is to include static and dynamic exercises on stable or unstable surfaces with eyes open or closed while standing in a bipedal or mono-pedal position (Granacher et al., 2011, DiStefano et al., 2009). Although this has been found to be effective in improving balance (Lin et al., 2007, Liu-Ambrose et al., 2008, Campbell et al., 1997, Suzuki et al., 2004), there is relative little information known about the cortical involvement and the muscle activity in the lower extremities with the common balance tasks used in balance training. In addition, there is no scientific guideline on the progression of balance exercises based on the difficulty of the balance tasks. Therefore, it is the aim of this study to examine the cortical response and the muscle activation of the hip and ankle muscles during eight common balance-training tasks. We hypothesized that the postural sway, the cortical response and the muscle activation of the hip and ankle muscles of the balance tasks would be significantly different from that of the control task. Balance exercises were ranked in the order of the difficulty based on the postural sway to provide evidence-based paradigm for the progression of a balance program.

Approaches of the Study

Numerous studies have shown the integral role of the central nervous system in the postural control. Balance exercises were used routinely to challenge the central nervous system in integrating the sensorimortor information. The aim of this study is to understand the cortical and motor response during eight balance tasks used commonly in balance training. To understand the motor response during the balance exercises, we first investigated the changes in the muscle activity of hip and ankle, and the postural sway during eight common balance tasks in Chapter 2 of this dissertation. The eight balance tasks were then ranked in the order of difficulty to establish an evidence-based paradigm for the progression of balance exercises. To understand the cortical involvement in these eight balance tasks, we examined that cortical activity of 3 wave bands (alpha, beta and sigma) during the eight balance tasks in Chapter 3 of this dissertation.

Significance of the Study

Balance exercises are used routinely to restore balance control in elderly but it is also beneficial to other variety of populations, nevertheless, the exercises used in the balance program are very diverse and little is known about the cortical involvement and the muscle activities of the lower extremity during the common balance tasks used in sensorimotor training. In addition, there is no scientific guideline on the progression of balance exercises based on the difficulty of the balance tasks. The results of this study contribute to the understanding of the cortical and motor responses during static balance tasks commonly used in sensorimotor training. In this study, evidence was provided in the progression of balance exercises and baseline data was established for future studies on other specific cohort of population.

CHAPTER TWO

POSTURAL SWAY AND ELECTROMYOGRAPHY ANALYSIS OF HIP AND ANKLE MUSCLES DURING EIGHT BALANCE TRAINING TASKS

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Abstract

Aims: This study examined how vision, base of support and surface compliance affected postural sway and electromyography (EMG) activity of hip and ankle muscles during eight balance training tasks in young adults.

Methods: Postural sway and EMG activity of gluteus maximus, gluteus medius, tibialis anterior and medial gastrocnemius were measured in 17 subjects during eight balance tasks with eyes open or closed, feet in tandem or apart and on foam or a firm surface.

Findings: Postural sway and EMG activity of hip and ankle muscles were significantly affected by the alteration of vision, surface compliance or base of support during eight balance tasks ($p < .05$). More increases were found when 2 or 3 of the sensory factors were altered in a task.

Conclusion: Our results suggested that balance training should start with alteration of one sensory factor by first altering the somatosensory input (base of support then the surface compliance), and followed by excluding the visual input. Then, it should be progressed by altering two then three sensory factors. Specific balance exercises are suggested based on the task difficulty. A balance program should include exercises to strengthen hip and ankle muscles to facilitate the postural control in static balance tasks.

Key words: balance exercise, EMG, postural sway, vision, foam, base of support

Introduction

Falls are one of the most prevalent causes of injury and death in the elderly population. One in every three adults ages 65 and older falls each year (Hausdorff et al, 2001). In 2010, 2.4 million non-fatal fall injuries in older adults were treated in emergency rooms (CDC, 2010), and over 20,000 older adults died from unintentional fall injuries (CDC, 2009). The elderly have displayed greater postural sway, which is associated with a greater risk of falling (Maki et al, 1994; Fernie et al, 1982).

Postural control is fundamental in the maintaining of balance. The central nervous system (CNS) is essential in integrating the afferent information from the vestibular, visual and somatosensory systems (Peterka, 2002; Horak and Shupert, 2000). Numerous studies have shown that stimulation of any of the three sensory systems evoked body sway (Kavounoudias et al, 1999; Day et al, 1997; Jeka et al, 1997). Studies have shown that there was a higher degree of postural sway when vision was compromised (Anand et al, 2003; Liaw et al, 2009). Cawsey et al. (2009) have further established the importance of vision on the postural stability on compliant surfaces. Diminished somatosensory function was also linked to the increase in postural sway (Shaffer and Harrison, 2007). Somatosensory information from the ankle and feet was found to be important in postural control (Kennedy and Inglis, 2002). To reduce the reliance of somatosensory information, foam balance tasks have been used in balance training to induce sway (Vuillerme and Pinsault, 2007); the effect was intensified when eyes were closed (Patel et al, 2011).

While maintaining balance involves the integration of the sensory information in the CNS, the motor system is also important in effective postural control (Johansson and Magnusson, 1991). The musculoskeletal system is essential in matching the external torque from the gravity or external perturbation, with the torque developed by the muscles (Balasubramaniam and Wing, 2002). Laughton et al. (2003) have shown a correlation between muscle activity at the ankles and the short-term postural sway. Other studies have also reported an association between the increase in body sway and weakness of the lower legs especially ankle doriflexors (Woollacott et al, 1986; Lord et al, 1991).

Studies have shown that postural control is highly adaptable and can be improved through balance training (Granacher et al, 2010; Granacher et al, 2011b). Balance exercise has shown to reduce rate and risk of falls (Madureira et al, 2007; Gillespie et al, 2009). Sherrington et al (2008) reported a 17% reduction in the fall risk when balance training is included in the exercise program, and the most effective balance programs is the one that challenged balance to a high extent . The exercises and tasks included in the balance program are greatly diverse; even Tai Chi is considered to be useful for balance training (Liu and Frank, 2010; Huang et al, 2010). There are few scientific guidelines in prescribing the balance exercises (Granacher et al, 2011a; Muehlbauer et al, 2012). Many clinicians have adopted individualized approaches based on physical assessment findings to prescribe exercises for balance (Haas et al, 2012). Yet, the general guideline for balance exercises is to include static and dynamic exercises on stable or unstable surfaces with eyes open or closed while standing in bipedal or mono-pedal position (Granacher et al., 2011a; DiStefano et al, 2009). This has been found to be effective in improving balance (Liu-Ambrose et al, 2008; Lin et al, 2007), but there is no evidence that other training paradigm might be better or evidence of the stress on muscles during balance tasks. In addition, there is no scientific guideline on the progression of balance exercises needed for training based on the difficulty of the balance tasks. Therefore, the aim of this study was to rank the difficulty of the standing balance tasks commonly used in balance training by examining the postural sway and activity of the hip and ankle muscles during eight common balance-training tasks. We hypothesized that vision, base of support (BOS) and surface compliance (Surface) would significantly affect postural sway and the muscle activity of hip and ankle muscles. The goal was to establish an evidence-based paradigm for the progression of balance program and to establish a baseline for future studies on the elderly and other specific cohort of population.

Subjects

Seventeen healthy young subjects (9 males, 8 females) free of any headaches, diabetes mellitus, and orthopedic or neurological condition were recruited. Subjects were sedentary individuals that were not participating in any balance exercises regularly. Subjects were instructed not to take any medication or central nervous stimulants that might affect their balance the day before the study. The general characteristics of the subjects are shown in Table 1. The experimental protocol approved by the Institutional Review Board of Loma Linda University was explained to each subject and the subjects gave their written informed consent for the study.

Table 1. Mean ± SD of the general characteristics by gender

	Age‡ (years)	**Height‡ (cm)**	**Weight* (kg)**
Female (n = 8)	26.4 ± 2.4	165.4 ± 9.3	62.8 ± 14.2
Male (n = 9)	27.8 ± 3.4	173.9 ± 6.1	78.9 ± 15.1
p-value	0.37	0.06	0.04

‡: Independent t-test.
*: Mann-Whitney U-test

Methods

Measurement of Postural Sway

The displacement of the subject's center of pressure was measured using a balance platform of 1 m by 1 m in size and 0.1 m in height (Petrofsky et al, 2009). Four stainless steel bars, each with four strain gauges, were mounted at the four corners under the platform (TML Strain Gauge FLA-6, 350-17, Tokyo, Japan). The output of the 4 Wheatstone strain gauge bridges was amplified by BioPac 100C low-level bio-potential amplifiers and was recorded on a BioPac MP-150 system through a 24-bit A/D converter. The sampling rate was 2000 samples per second (Petrofsky et al., 2009).

To calculate the load and the center of the pressure of the force on the platform, the output of the four sensors was used to measure the X and Y coordinates of the center of gravity of the subject. This data was converted to a movement vector giving a magnitude and angular displacement. By averaging the vector magnitude over 6 seconds, mean and standard deviation (SD) were obtained for this measure. From this, the Coefficient of Variation (CV) was calculated (SD/Mean x 100) as a measure of the postural sway (Petrofsky et al., 2009). The average CV of each task was then determined by averaging the CVs of the 3 trials.

Measurement of Muscle Activity

Surface electrical muscle activity of the gluteus maximus (GMAX), gluteus medius (GMED), tibialis anterior (TA) and medial gastrocnemius (GAST) of subject's dominant leg were measured using 2 dual-channel wireless electromyogram (EMG) (Model BN-EMG2) (BioPac systems, Inc., Goleta, CA). The electromyogram of two muscles was paired to a receiver via one transmitter module. Two bipolar vinyl adhesive EMG electrodes (Kendall Medi Trace 200, Tyco Healthcare Group LP, Mansfield, MA) were placed on each selected muscle with one on the muscle belly of the muscle and the other one placed immediately distal to it. A ground electrode was placed on one of the selected muscles. The electrical output of the muscles was amplified with a bio-potential amplifier (Model BN-EMG2-R, BioPac Systems Inc., Goleta, CA) with a gain of 2000 and frequency response was filtered from DC to 1000Hz. The data was digitized with a 24-bit analog to digital converter, sampled at a frequency of 1000 samples per second and amplified 5,000 times using the MP-150 system (BioPac Systems Inc., Goleta, CA).

The amplitude of the maximum voluntary isometric contraction (MVC) of the selected muscle was recorded while the subject exerted maximum contractions against manual resistance for 3 seconds. The average MVC of each muscle was then used to normalize the EMG data collected during the balance tasks (Soderberg and Knutson, 2000). The EMG data was expressed as a percentage of the MVC. The average normalized MVC of each muscle in each of the balance tasks was then determined by averaging the data from the 3 trials. Average EMG activity of all the muscles (TEMG) was calculated by combining the average normalized MVC of the 4 muscles. Total muscle work (TEMG work) was then determined by multiplying the TEMG activity with the Coefficient of Variation (CV) of the postural sway. Group muscle work is used as an index of work since sway is a measure of distance moved and percentage of MVC is a measure of relative force.

Balance Tasks

Eight quiet standing balance tasks, each lasting for 6 seconds, were included in this study. To challenge the somatosensory input, 2 different feet positions (feet apart & tandem), and 2 different surface compliances (firm surface & foam) were used. To challenge the visual input, 2 levels of vision (eyes open & closed) were used in the balance tasks. Aeromat balance block with size 16 x 19 x 2.5 inches (AGM Group / Aeromat Fitness Product, Fremont, CA) was placed on top of the balance platform and was used as the foam surface. The eight balance tasks are listed in Table 2.

- Standing with feet apart on a firm surface with eyes open (FAEO-FIRM) and eyes closed (FAEC-FIRM).
- Standing with feet in tandem on a firm surface with eyes open (TEO-FIRM) and eyes closed (TEC-FIRM).
- Standing with feet apart on a foam with eyes open (FAEO-FOAM) and eyes closed (FAEC-FOAM).
- Standing with feet in tandem on a foam with eyes open (TEO-FOAM) and eyes closed (TEC-FOAM).

Table 2. Eight balance tasks in the study.

	Firm Surface		Foam	
Feet position	**Eyes open**	**Eyes closed**	**Eyes open**	**Eyes closed**
Feet apart	FAEO-FIRM (Control task)	FAEC-FIRM	FAEO-FOAM	FAEC-FOAM
Tandem	TEO-FIRM	TEC-FIRM	TEO-FOAM	TEC-FOAM

Procedures

Baseline demographic data including age, height, weight and side of dominance were collected from each subject at the beginning of the study. EMG electrodes were placed at the GMAX, GMED, TA and GAST of the subject's dominant leg. Maximum voluntary isometric contraction (MVC) of each muscle was measured by having subjects to exert maximum contraction against manual resistance for 3 seconds. The test was repeated 3 times for each selected muscle. A 1-minute rest period was given in between the trials. Subjects started with the control task, in which subjects stood with feet apart on the balance platform for 6 seconds. Their feet were aligned with the centers of the calcaneus the same distance as that of the two Anterior Superior Iliac Spine. They were instructed to fix their eyes on a target on the wall with arms crossed in front of their chests. The task was repeated 3 times. To minimize fatigue, subjects were instructed to hold onto a chair to rest in standing for 10 seconds between the tasks. Thereafter, the subject was randomized to the rest of the balance tasks on firm surface. Then an Aeromat balance block was placed on top of the balance platform and data was collected during the randomized balance tasks on the foam.

Data Analysis

Data was summarized using descriptive statistics. Mean and standard deviation of age and height by gender were compared using independent t-test. Mann-Whitney U-test was used to compare the weight by gender. The Kolmogorov-Smirnov test was used to assess the normality of the variables. Repeated measures analysis of variance (ANOVA) was used to examine the effect of Vision, Surface and BOS on the postural sway. To test for significant differences, Bonferroni test was used. The results were considered significant if $p < .05$.

Results

No difference was found in any of the measured parameters comparing male and female ($p > .05$) except EMG activity of GMED, therefore, only average result of all the subjects was showed.

EMG Activity of Hip and Ankle Muscles

The TEMG ranged from 24.3% to 170.0% of the MVC (Figure 1). The TEMG work ranged from 156.2 units to 4558.0 units across the balance tasks (Figure 2). The EMG activity of GMAX ranged from 3.2% to 10.5% of the MVC, 3.9% to 17.0% for GMED, 1.2% to 37.6% for TA and 15.7% to 104.9% for GAST. The highest TEMG and individual EMG was found in task TEC-FOAM (Table 3).

When compared to the control task (Table 3), TEMG activity was significantly higher by 40% to 601% on foam regardless of vision and base of support, and in tandem stand regardless of surface compliance and vision condition ($p < .005$). TEMG work was also significantly higher in all the balance tasks on the foam, and in task TEC-FIRM when compared to the control task ($p < .05$). EMG activity of GMAX increased significantly in tandem stand with vision excluded on firm surface (by 66%, $p < .01$) and on foam (by 230%, $p < .01$). EMG activity of GMED and TA were significantly higher in all the tasks with tandem stand ($p < .01$, $p < .001$, respectively). In task FAEC-FOAM, TA EMG activity showed a significant increase of 69% when compared to the control task ($p = .04$). GAST EMG activity was significantly higher on foam by 47% to 566% regardless of vision and base of support ($p < .05$), and in tandem stand by 166% to 566% regardless of vision condition ($p < .01$).

Influence of Vision on the EMG Activity (Table 4)

Vision affected the TEMG activity and TEMG work significantly ($p < .001$). When standing in tandem on the firm surface, the TEMG work was higher by 232% when eyes were closed ($p < .01$) whereas when standing in tandem on foam, eyes closed increased the TEMG work by 364% ($p < .001$).

Vision also affected the EMG activity of the selected hip and ankle muscles significantly ($p < .001$). When standing on foam with feet in tandem, there was a 94% increase in the GMAX EMG activity when eyes were closed ($p < .01$). An increase of 75% in the GMED muscle activity was observed when eyes were closed in the tandem stand on foam, yet with no significant difference. There was a significant increase of 130% in the TA EMG activity in tandem stand when eyes were closed on firm surface ($p = .005$) and 197% on foam ($p < .001$). GAST EMG activity showed a significant increase of 63% when eyes were closed in tandem standing on firm surface ($p < .01$) and 90% on foam ($p = .001$).

Influence of Surface Compliance on the EMG Activity (Table 4)

Foam increased the TEMG activity and TEMG work significantly ($p < .001$). When compared to the firm surface, standing on foam with feet apart increased the TEMG work significantly by 73% to 144% (eyes open with $p = .04$, eyes closed with $p = .02$), whereas in tandem standing on foam, it increased by 244% with eyes closed ($p < .001$).

Foam surface also affected the EMG activity of hip and ankle muscles significantly ($p < .005$). GMAX and GMED EMG activity increased by 99% and 75% respectively when standing in tandem with eyes closed on foam was compared to that on the firm surface, yet with no significant differences. TA EMG activity was significantly higher by 91% when standing on foam with feet apart and eyes closed ($p < .01$); whereas in tandem standing on foam with eyes closed, a 131% increase was found ($p < .001$). The EMG activity of GAST was significantly higher by 47% when standing on foam with feet apart and eyes open ($p = .02$), and 59% with eyes closed ($p = .01$), whereas in tandem stand on foam, a significant increase of 54% was found when compared to the firm surface ($p = .04$).

Influence of Base of Support on the EMG Activity (Table 4)

Base of support affected the TEMG and TEMG work significantly ($p < .001$). In standing on the firm surface, there were 150% and 267% more TEMG in tandem stand with eyes open and eyes closed respectively compared to that with feet apart ($p < .001$). When standing on foam, there were 144% and 315% greater TEMG in tandem stand with eyes open and eyes closed respectively compared to that with feet apart ($p < .001$). There were increases in TEMG work by 263% and 631% when tandem stand with eyes open ($p < .01$) and eyes closed ($p < .001$) respectively, were compared to that with feet apart on foam.

Base of support affected the EMG activity of hip and ankle muscles significantly ($p < .001$). GMAX EMG activity increased significantly by 63% when tandem standing on firm surface with eyes closed was compared to that with feet apart ($p = .02$), whereas in tandem standing with eyes closed on foam, a significant increase of 169% was demonstrated ($p < .01$). For the GMED EMG activity, a significant increase of 89% to 207% was found in tandem stand when compared to that with feet apart ($p < .05$). EMG activity of TA increased significantly by 417% to 1522% in tandem stand when compared to that with feet apart ($p < .001$), whereas the EMG activity of GAST was significantly higher by 138% to 270% in tandem stand ($p < .01$).

Influence of 2 or 3 Factors altered on the EMG Activity (Table 4)

The TEMG was significantly higher when 2 factors were altered in the tasks ($p < .001$). There were 3 times and 10.4 times increases in the TEMG work when both vision and the surface compliance were altered in standing with feet apart ($p = .001$) and in tandem ($p < .001$) respectively. When both vision and base of support were altered on firm surface and on foam, the TEMG work increased by 7.5 times ($p = .04$) and 15.8 times ($p < .001$) respectively. When base of support and the compliance of the supporting surface were changed, the TEMG work increased by 5.3 times and 16.8 times with eyes open ($p = .001$) and eyes closed ($p < .001$) respectively. When 3 factors were altered, the TEMG activity increased significantly ($p < .001$). There was a 28.2 times increase in the TEMG work in TEC-FOAM when compared to that in the control task ($p < .001$).

GMAX EMG muscle activity was significantly higher by 0.7 to 2.2 times when 2 factors were altered in the tasks ($p < .05$). When 3 factors were altered, it increased significantly by 2.3 times ($p < .01$).

GMED EMG muscle activity was significantly higher when 2 factors were altered in the tasks. When vision and base of support were changed, GMED EMG activity increased significantly by 1.5 to 2.3 times ($p < .05$). When base of support and surface compliance were altered, it was significantly higher by 1.5 to 3 times ($p < .05$). When 3 factors were altered, it increased significantly by 3.3 times ($p < .01$).

TA EMG muscle activity was significantly higher when 2 factors were altered in the tasks. When vision and base of support were changed, TA EMG activity increased by 10.9 to 22.4 times ($p < .001$). When vision and the surface compliances were altered, it increased by 0.7 to 4.3 times ($p < .05$). When the base of support and the surface compliance were altered, it was higher by 8.2 to 30 times ($p < .001$). When 3 factors were altered, the EMG activity of TA was significantly greater by 26.4 times ($p < .001$).

The EMG muscle activity at GAST was higher when 2 factors were altered in the tasks. When vision and the base of support were changed, the EMG activity of GAST increased by 3.3 to 3.5 times ($p < .001$). When vision and the surface compliance were altered, EMG activity of GAST increased by 0.9 to 1.5 times ($p < .05$). When the base of support and the surface compliance were altered, the EMG activity of GAST was higher by 2.5 to 4.7 times ($p < .01$). When 3 factors were altered, the EMG activity of GAST was significantly greater by 5.7 times ($p < .001$).

Table 3. Mean ± SEM of the EMG activity of Gluteus Maximus (GMAX), Gluteus Medius (GMED), Tibialis Anterior (TA), Medial Gastrocnemius (GAST), the average EMG activity of all 4 muscles (TEMG) and the Coefficient of Variation of the postural sway (CV) of the balance tasks. * indicates significant difference ($p < .05$) when compared to the control task, FAEO-FIRM.

	BALANCE TASKS							
Muscle	FAEO-FIRM (Control)	FAEC-FIRM	FAEO-FOAM	FAEC-FOAM	TEO-FIRM	TEO-FOAM	TEC-FIRM	TEC-FOAM
Group muscle	24.3 ± 2.3	27.1 ± 3.1	34 ± 3.5 *	40.9 ± 4.8 *	60.6 ± 6.1 *	83 ± 8.7 *	99.3 ± 9.2 *	170 ± 13.6 *
GMAX	3.2 ± 0.6	3.2 ± 0.6	4.1 ± 0.8	3.9 ± 0.9	4.3 ± 0.6	5.4 ± 0.9	5.3 ± 0.7 *	10.5 ± 1.7 *
GMED	3.9 ± 0.7	4.3 ± 0.9	5.2 ± 0.9	5.5 ± 1.0	7.4 ± 0.8 *	9.7 ± 1.2 *	9.7 ± 1.3 *	17.0 ± 3.1 *
TA	1.3 ± 0.2	1.2 ± 0.1	1.6 ± 0.2	2.3 ± 0.4 *	7.1 ± 0.9 *	12.8 ± 1.8 *	16.4 ± 2.4 *	37.6 ± 3.7 *
GAST	15.8 ± 2	18.4 ± 2.5	23.2 ± 3.1 *	29.2 ± 4.2 *	41.8 ± 5.7 *	55.2 ± 8 *	68 ± 7.9 *	104.9 ± 13.6 *
CV	6.2 ± 0.8	10.1 ± 1.4	8.9 ± 1.2	16.7 ± 1.9 8 *	6.5 ± 2.0	12.0 ± 1.3	12.0 ± 2.1	27.2 ± 2.2 *

Table 4. Comparison of balance tasks to illustrate the effect of the sensory factors.
* $p < .05$

Factors	Tasks	CV	Gmax	Gmed	TA	Gast	TEMG
Vision (EC vs. EO)	FAEC-FIRM vs. FAEO-FIRM						
	TEC-FIRM vs. TEO-FIRM				*	*	*
	FAEC-FOAM vs. FAEO-FOAM	*					
	TEC-FOAM vs. TEO-FOAM	*	*		*	*	*
Surface (Foam vs. Firm)	FAEO-FOAM vs. FAEO-FIRM					*	*
	FAEC-FOAM vs. FAEC-FIRM				*	*	*
	TEO-FOAM vs. TEO-FIRM						
	TEC-FOAM vs. TEC-FIRM	*			*	*	*
BOS (Tandem vs. FA)	TEO-FIRM vs. FAEO-FIRM			*	*	*	*
	TEC-FIRM vs. FAEC-FIRM		*	*	*	*	*
	TEO-FOAM vs. FAEO-FOAM			*	*	*	*
	TEC-FOAM vs. FAEC-FOAM	*	*	*	*	*	*
Combination of 2 factors							
Vision & Surface	FAEC-FOAM vs. FAEO-FIRM	*			*	*	*
	TEC-FOAM vs. TEO-FIRM	*	*		*	*	*
Vision & BOS	TEC-FIRM vs. FAEO-FIRM		*	*	*	*	*
	TEC-FOAM vs. FAEO-FOAM	*	*	*	*	*	*
BOS & Surface	TEO-FOAM vs. FAEO-FIRM			*	*	*	*
	TEC-FOAM vs. FAEC-FIRM	*	*	*	*	*	*
Combination of 3 factors							
Vision & Surface & BOS	TEC-FOAM vs. FAEO-FIRM	*	*	*	*	*	*

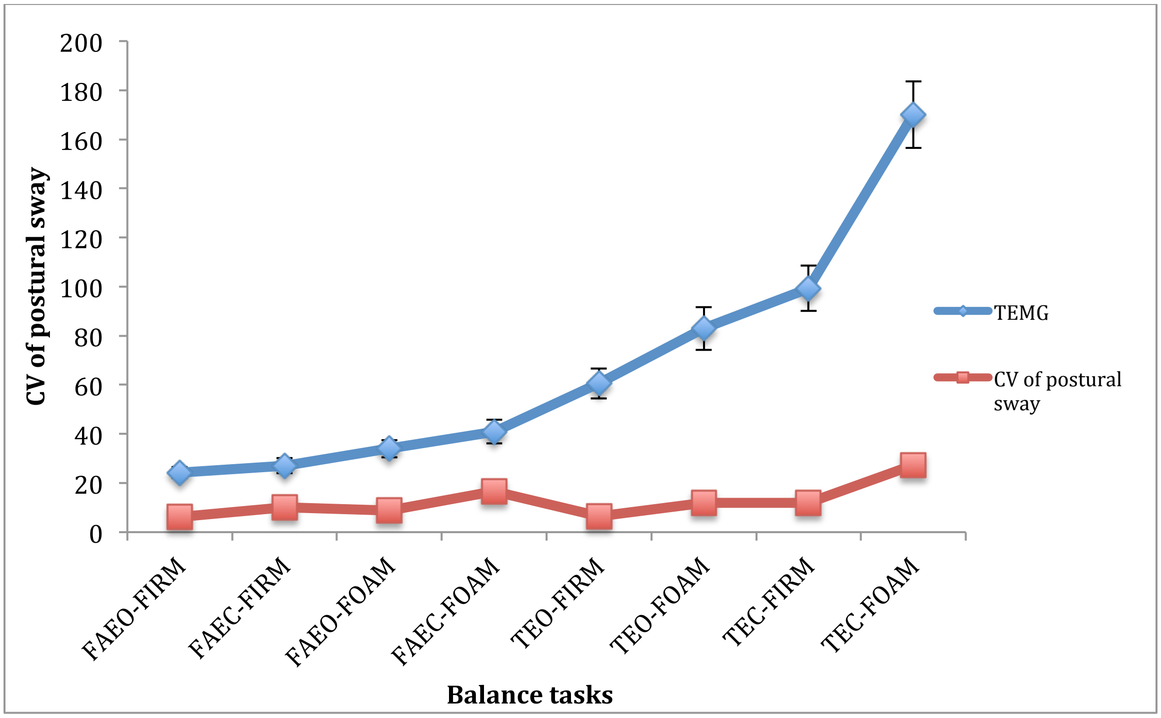

Figure 1. Mean ± SEM of the TEMG and the coefficient of variation (CV) of the postural sway with the balance tasks.

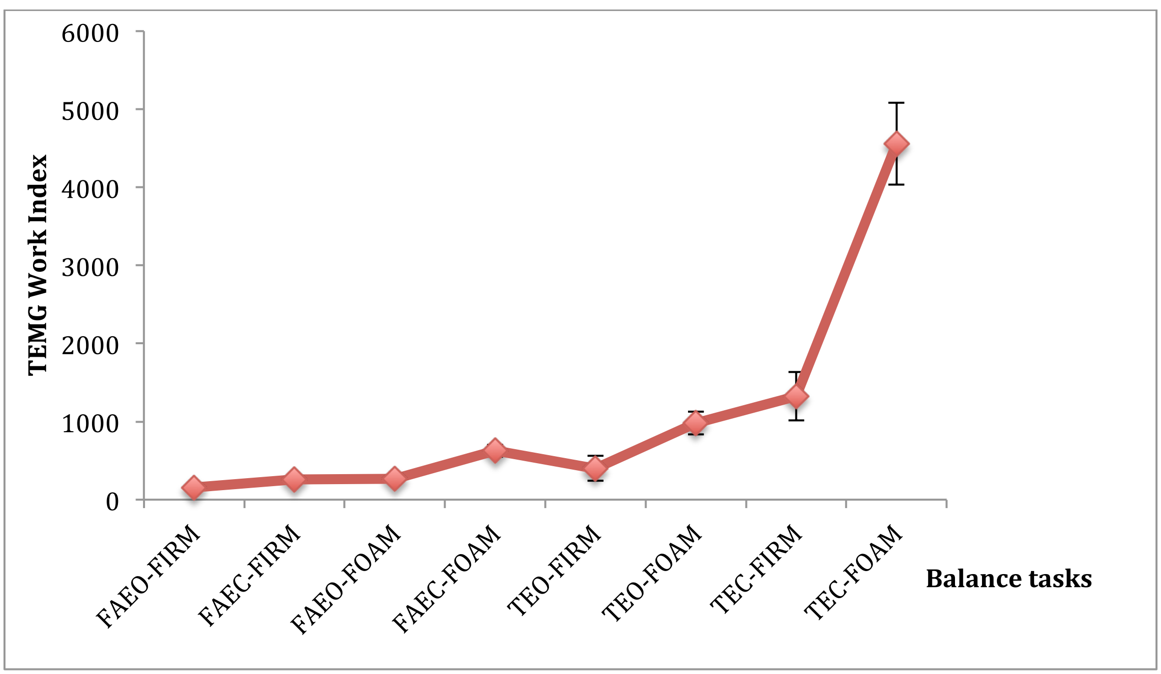

Figure 2. Mean ± SEM of the TEMG work (TEMG activity x CV of the postural sway) with the balance tasks.

Postural Sway

Influence of Sensory Factors on Postural Sway

As shown in Table 4, vision affected the postural sway significantly ($p < .001$). When eyes were closed in standing on foam, postural sway increased significantly by 87% with feet apart ($p < .01$) and 126% in tandem standing ($p < .001$). The compliance of the standing surface also affected postural sway significantly ($p < .001$). Postural sway was significantly higher by 127% in standing on foam compared to that on the firm surface while standing in tandem with eyes closed ($p < .01$). Base of support affected postural sway significantly ($p = .04$). When standing with eyes closed on foam, postural sway was higher in tandem stand by 62.9% when compared to that with feet apart ($p = .03$). There was greater postural sway when 2 factors were altered. When vision and surface compliance were altered, postural sway was significantly higher by 1.7 times and 3.2 times in standing with feet apart ($p < .01$) and in tandem ($p < .001$) respectively. When vision and base of support were altered on foam, postural sway was significantly higher by 2.1 times ($p < .001$). When base of support and surface compliance were altered in tasks with eyes closed, postural sway was significantly higher by 1.7 times ($p = .001$). When 3 factors were altered, postural sway was significantly higher by 3.4 times ($p < .001$).

Ranks of the Balance Tasks

Postural sway in the balance tasks ranked in an increasing order of difficulty and the involvement of hip and ankle muscles are displayed in Figure 3 and 4. When compared to the control task, there was a 6% increase in postural sway with significantly higher EMG activity at GMED ($p < .001$), GAST ($p < .01$) and TA ($p < .001$) when base of support was altered in TEO-FIRM. A 44% increase in postural sway with a significant higher GAST EMG activity ($p = .02$) was observed when surface compliance was changed in FAEO-FOAM. When vision was altered in FAEC-FIRM, 63% more postural sway with no significant changes in leg muscles activity was displayed.

When 2 sensory factors were altered, postural sway increased by 94% and, hip and ankle muscle activities were significantly higher ($p < .01$) in TEC-FIRM (Base of support and vision altered); whereas in TEO-FOAM (Base of support and surface compliance altered), there was a 95% increase in postural sway and significantly more GMED ($p < .001$), GAST ($p < .01$) and TA ($p < .001$) muscle activities were observed. When vision and surface compliance were altered in FAEC-FOAM, postural sway increased significantly by 170% ($p < .01$) and GAST EMG activity was significantly higher ($p = .02$). When 3 sensory factors were altered in TEC-FOAM, the increase in postural sway became 340% ($p < .001$) and all the hip and knee muscle activity was significantly augmented ($p < .01$).

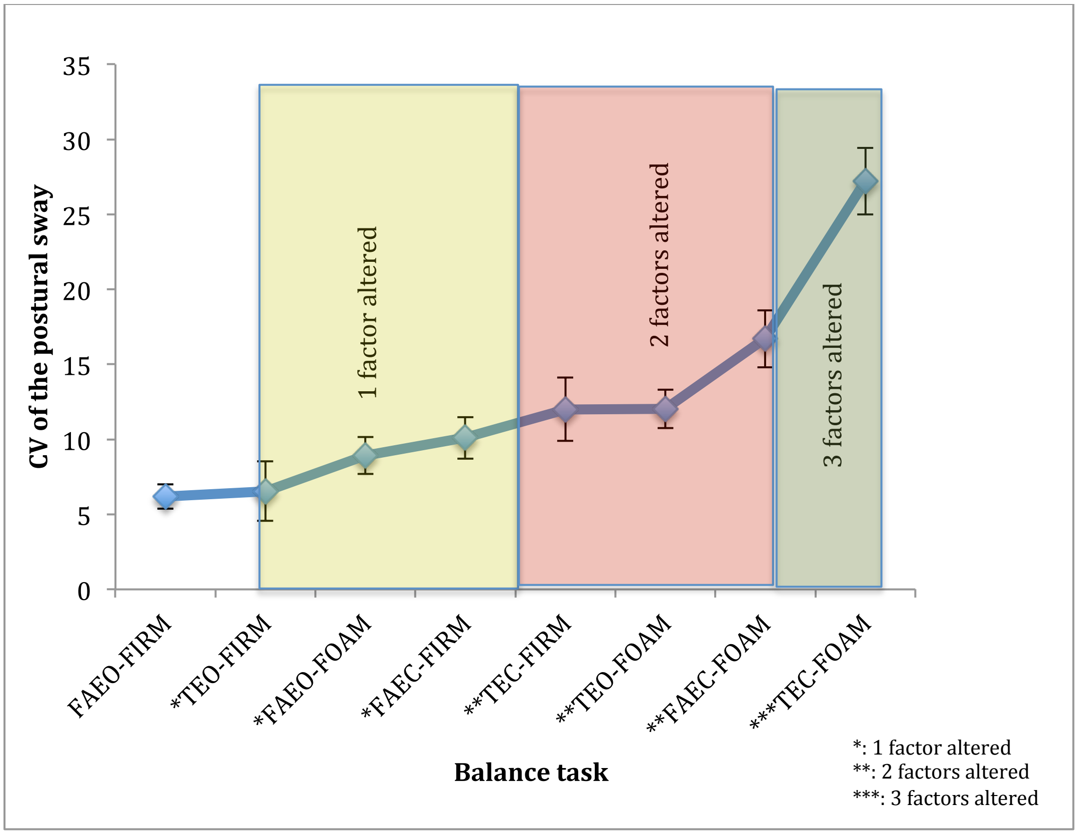

Figure 3. Mean ± SEM of postural sway (Coefficient of Variation of the postural sway) in 8 balance tasks.

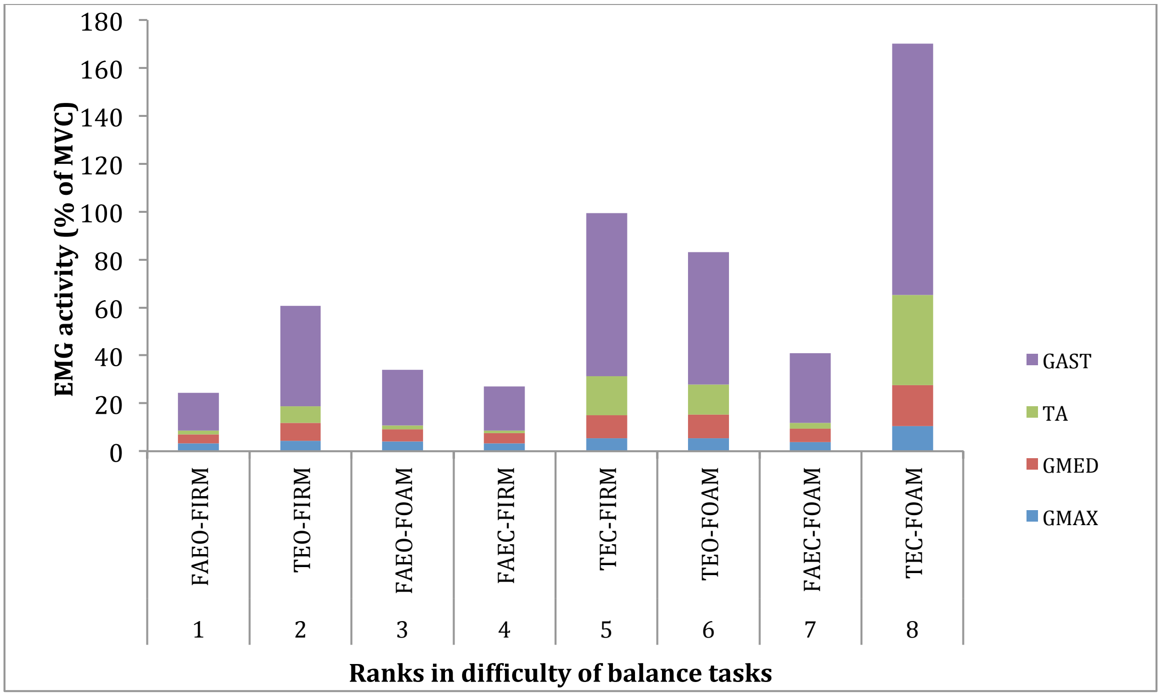

Figure 4. EMG activity of hip & ankle muscles during 8 balance tasks (Ranked in the order of increasing postural sway).

Discussion

Effective balance training challenges the integration of the sensory systems and the execution of muscular control through the motor system. Static balance exercises are used commonly in a balance-training program, however, little is known about those common static balance tasks. In this study, we examined how vision, base of support and surface compliance affected postural sway and EMG activity of hip and ankle muscles during eight common balance training tasks in young healthy adults to assess the severity of the challenge. Suggestions on the progression of the balance exercises based on the ranking of the tasks difficulty were given.

Vision, surface compliance or base of support significantly affected postural sway and muscle activity of hip and ankle in young healthy adults. More significant increases were found when 2 factors (vision and surface compliance) or 3 factors (vision, base of support and surface compliance) were altered simultaneously. GMED and TA EMG activity increased significantly in tandem standing regardless of vision and surface compliance; GMAX was recruited significantly only when vision was excluded in the above tasks; GAST EMG activity was significantly higher on foam regardless of vision and base of support, and in tandem stand regardless of the surface compliance and vision. Balance exercises can be progressed according to the rank of tasks difficulty. Strengthening of hip and ankle muscles is recommended in the postural control during the balance training.

Our study concurs with previous studies showing that postural sway was affected by vision (Singh et al, 2012), surface compliance (Jeka et al, 2004) and base of support (Muehlbauer et al., 2012). In addition, results support the study from Fransson et al (2007) showing that vision affected EMG activity of the lower legs and, foam affected the GAST EMG activity in regardless of the vision, but it only affected the TA EMG activity when eyes were closed. Amiridis et al (2003) have demonstrated the effect of base of support on the ankle EMG activity. Our study showed that both GMED and ankle EMG activity increased significantly with narrow base of support and when tasks became more challenging with eyes closed, the effect of base of support affected the GMAX EMG activity as well suggesting an increase in the use of both hip and ankle strategies in tasks with narrow base of support especially with eyes closed.

Postural sway and EMG activity of hip and ankle muscles were significantly higher when 2 or 3 factors were altered, which concurs with the findings from Bugnariu and Fung (2007). Subjects have to rely heavily on vestibular input when 2 factors (vision and somatosensory) were altered and both hip and ankle strategies were used for postural control as evidenced by the significant increase in EMG activity of the hip and ankle muscles. The challenge on the vestibular input was more pronounced when 3 factors were altered.

To the best of our knowledge, there is only one study that provided guidelines in the progression of balance training. Although the exercises they chose were different from our study's, Muehlbauer et al. (2012) suggested progression of balance exercises from easy (bipedal and step stance), to mild (tandem and monopedal stance with eyes opened) and then to hard (tandem and monopedal stance with eyes closed) stage. Our findings suggest that in the early stage of the balance training, only one sensory factor should be altered in the progression of the balance tasks. As balance improves, balance tasks should include the alteration of two sensory factors to challenge the postural stability. At the advanced balance challenge, three factors should be altered to increase the demand on the postural control. The following recommendations provide the guidelines in the progression of the balance training in an increasing order of difficulty. Specific balance tasks were included in the parentheses:

1. Start with the easiest task with vision (eyes open) and somatosensory (feet apart on firm surface) information present, (FAEO-FIRM).
2. Alter the somatosensory input by changing the base of support, (TEO-FIRM).
3. Alter the somatosensory input by changing the compliance of the supporting surface, (FAEO-FOAM).
4. Exclude the visual input by closing the eyes, (FAEC-FIRM).
5. Alter somatosensory (base of support) and visual (vision) inputs, (TEC-FIRM).

6. Alter 2 factors in somatosensory inputs (base of support and surface compliance), (TEO-FOAM).
7. Alter somatosensory (surface compliance) and visual inputs, (FAEC-FOAM).
8. Alter 3 factors (vision, base of support and surface compliance) in a task, (TEC-FOAM).

The data of the EMG activity suggests the significance of hip and ankle muscle activities in tasks on foam and tasks with tandem stand. Therefore, to design an effective balance program, it is imperative to include strengthening exercises of GMAX, GMED, TA and GAST, to ensure the progression of the balance tasks.

In our study, young healthy subjects were recruited; the results should not be extrapolated to other populations. Further study on older adults or patients is recommended. Furthermore, our sample size is small; a larger sample size is suggested in future study. In our study, the MVC was obtained by exerting maximum isometric muscle contraction against manual resistance. Though standardized verbal instruction was used in the study, variation in the subjects' performance and manual resistance applied were present. It is recommended to use an isokinetic dynamometer to obtain a more objective value of the MVC for each muscle in the future study.

Conclusions

This study showed that alteration of vision, surface compliance and base of support significantly affected the postural stability and the muscle activity of the hip and ankle muscles. Progression of balance training should start with alteration of one sensory factor by first altering the somatosensory input in changing the base of support then the surface compliance, and followed by excluding the visual input. Then, the program should be progressed to altering two followed by three sensory factors. Specific balance exercises were suggested based on the task difficulty. A balance program should include exercises to strengthen GMAX, GMED, TA and GAST to facilitate the postural control in static balance tasks. A comprehensive balance program should be based on a thorough evaluation to assess the specific sensory or motor impairments and it should include dynamic balance tasks that incorporate perturbation-based and multi-task balance activity.

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CHAPTER THREE

POSTURAL SWAY AND ELECTROENCEPHALOGRAPHY ANALYSIS OF CORTICAL ACTIVATION DURING EIGHT BALANCE TRAINING TASKS

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Summary

Background: Effective balance training induces adaptation in the central nervous system. The purpose of this study was to examine the cortical response in common sensorimotor and balance training tasks and to assess the electroencephalography (EEG) changes with different levels of task difficulty.

Material and Methods: Postural sway and EEG change of alpha, beta and sigma wave bands were measured in 17 subjects during eight progressively more difficult balance tasks with eyes open and closed, feet in tandem or apart and on form or a firm surface.

Results: EEG power of beta and sigma wave bands showed significant increases at the central and parietal area of the brain relative to the control tasks when eyes were open ($p < 0.05$). The cortical involvement decreased as the task became more difficult with vision and somatosensory information altered. When the task became more challenging with vision, base of support and surface compliance altered, the power of the EEG in the beta and sigma bands increased significantly ($p < 0.05$).

Conclusions: This study demonstrated cortical involvement in static balance tasks commonly used in sensorimotor training. The results suggest that there was increased subcortical control with increase task difficulty.

Keywords: EEG, posture, sensorimotor training, balance

Background

Maintaining an upright posture is a complex motor skill based on the integration of dynamic sensorimotor information.[1] It was assumed that postural regulation is under the control of subcortical structures of the cerebrum and the spinal cord,[2] but more studies have emerged to suggest cortical involvement in the postural response. With positron emission tomography (PET), the cerebellum vermis and the prefrontal cortex were shown to be significantly involved in postural control.[3] Using a functional near-infrared spectroscopic analyzer, Mihara and colleagues showed activation in the prefrontal cortex after external perturbation regardless of the auditory warning preceding the task.[4] Using functional magnetic resonance imaging (fMRI), Jacobs and colleagues reported cortical involvement in the control of postural tasks and;[5] Goble and colleagues demonstrated central processing of proprioceptive signals from the foot for balance control.[6] Studies using electroencephalography (EEG) have also shown that movement-related cortical potentials were present preceding the onset of self-paced initiation of postural sway and after voluntary limb movement.[7,8] Adkin and colleagues postulated that there was an increase in cortical negative potential following an application of nudges during gait or surface translation.[9] Jacobs and colleagues reported the same phenomenon during perturbation with cues suggesting that cerebral cortex contributed to the modification of upcoming postural responses to external perturbation when provided with pre-warning cues.[10] Mochizuki and colleagues also reported that cortical activity was observed prior to and following predictable and un-predictable perturbation of balance.[11]

It has been well documented that balance training improves postural control.[12,13] Balance training has also been shown to induce supraspinal adaptation.[14] Studies have shown that short-term motor skill training was associated with cortical adaptation.[15,16] Taube and colleagues have reported a decrease in corticospinal and cortical excitability with four weeks of balance training and suggested that the balance improvement relied mostly on the supraspinal adaptation.[14] In addition, other studies have demonstrated an association between reduced supraspinal excitability and improvement in balance performance with balance training and suggested an enhancement of subcortical control of muscles.[17,18]

Balance-training programs are very diverse. The general guideline for balance exercises is to include static and dynamic exercises on stable or unstable surfaces with eyes open or closed while standing in a bipedal or mono-pedal position.[19,20] However, specific sensorimotor exercises are used commonly by clinicians to address the deficit in sensorimotor integration in postural control. While these balance exercises are presumed to induce adaptation in the central nervous system, there is no scientific evidence to show any cortical involvement in the these exercises. Most of the studies that investigated the neural response associated with balance training used electrophysiological and imaging techniques. While imaging techniques (e.g. fMRI, PET) have excellent spatial resolution and provide great access to subcortical areas, they only measure the cerebral blood flow during the performance of the tasks. The EEG provides more accurate temporal resolution. Previous studies have examined only the changes of event-related motor potential preceding and after transient perturbation. To the best of our knowledge, there are no studies on the power change of the cortical activity during static standing balance tasks that are commonly used in sensorimotor training. Therefore, the aim of this study was to examine the cortical response in the common balance training tasks. We hypothesized that there would be measurable changes in the power of the cortical response with changes in the difficulty of the tasks.

Material and Methods

Subjects

Seventeen healthy young subjects (9 males, 8 females) free of headaches, diabetes mellitus, and orthopedic or neurological conditions were recruited. Subjects were sedentary individuals who did not participate in any regular balance exercises. Subjects were instructed not to take any medication or central nervous stimulants that might affect their balance the day before the study. The general characteristics of the subjects are shown in Table 1. The experimental protocol, approved by the Institutional Review Board of Loma Linda University, was explained to each subject and the subjects gave their written informed consent for the study.

Measurement of Postural Sway

The displacement of the subject's center of pressure was measured using a balance platform of 1 m by 1 m in size and 0.1 m in height.[21] Four stainless steel bars, each with four strain gauges, were mounted at the four corners under the platform (TML Strain Gauge FLA-6, 350-17, Tokyo, Japan). The output of the 4 Wheatstone strain gauge bridges was amplified with BioPac 100C low-level bio-potential amplifiers and recorded on a BioPac MP-150 system through a 24-bit A/D converter. The sampling rate was 2000 samples per second.[21]

To calculate the load and the center of the pressure of the force on the platform, the output of the four sensors was used to measure the X and Y coordinates of the center of gravity of the subject. This data was converted to a movement vector giving a magnitude and angular displacement. By averaging the vector magnitude over 6 seconds, mean and standard deviation (SD) were obtained for this measure. From this, the Coefficient of Variation (CV) was calculated (SD/Mean x 100) as a measure of the postural sway.[21] The average CV of each task was then determined by averaging the CVs of the 3 trials.

Measurement of Cortical Response

The B-Alert X10 wireless EEG 9 channels headset (Advanced Brain Monitoring Inc., Carlsbad, CA, USA) integrated with the AcqKnowledge MP-150 acquisition software (BioPac systems, Inc., Goleta, CA) was used to acquire the EEG data from three channels (Fz, Cz and POz). Linked mastoids were served as reference and electrode impedance was kept below 40kΩ. The data was sampled at a frequency of 256 samples per second and was filtered with a band-pass filter (0.5-65 Hz) before using the 16-bit analog-to-digital conversion. Notch filters at 50, 60, 100 and 120 Hz were applied to remove environmental artifacts. Eye blinks and excessive muscle activity were identified and decontaminated by the system.

All uncontaminated EEG data for each task was epoched into 1-second blocks with the B-Alert Software version 2.90 (Advanced Brain Monitoring Inc., Carlsbad, CA, USA). The absolute power spectral densities (PSD) of alpha (8-12 Hz), beta (13-19 Hz) and sigma (30-40 Hz) frequency bands were computed for each task using a Fast-Fourier transform with a 50% overlapping Kaiser window. It was then divided by the absolute PSD of the corresponding frequency band in the control task. This provides the percentage of the PSD of each frequency band relative to the control task in each individual task. The average PSD was then computed using the data from the 3 trials.

Balance Tasks

Eight quiet standing balance tasks, each lasting for 6 seconds were included in this study [22]. To challenge the somatosensory input, 2 different feet positions (feet apart & tandem), and 2 different surface compliances (firm surface & foam) were used. To challenge the visual input, 2 levels of vision (eyes open & closed) were used in the balance tasks. Aeromat balance block with size 16 x 19 x 2.5 inches (AGM Group, Aeromat Fitness Product, Fremont, CA) was placed on top of the balance platform and was used as the foam surface. The eight balance tasks are listed in Table 2.

- Standing with feet apart on a firm surface with eyes open (FAEO-FIRM) and eyes closed (FAEC-FIRM).
- Standing with feet in tandem on a firm surface with eyes open (TEO-FIRM) and eyes closed (TEC-FIRM).
- Standing with feet apart on a foam surface with eyes open (FAEO-FOAM) and eyes closed (FAEC-FOAM).
- Standing with feet in tandem on a foam surface with eyes open (TEO-FOAM) and eyes closed (TEC-FOAM).

Procedures

Baseline demographic data including age, height, weight and side of dominance were collected from each subject at the beginning of the study. The B-Alert X10 wireless EEG 9 channels headset was placed on the skull. Bilateral mastoids were linked as reference. Electrode impedance was then checked. Subjects started with the control task, in which they stood with feet apart on the balance platform for 6 seconds. Their feet were aligned with the centers of the calcaneus the same distance as that of the two Anterior Superior Iliac Spine. They were instructed to fix their eyes on a target on the wall with arms crossed in front of their chests. The task was repeated 3 times. To minimize fatigue, subjects were instructed to hold onto a chair to rest in standing for 10 seconds between the tasks. Thereafter, the subject was randomized to the rest of the balance tasks on the firm surface. Then an Aeromat balance block was placed on top of the balance platform and data was collected during the randomized balance tasks on the foam.

Data Analysis

Data was summarized using descriptive statistics. The Kolmogorov-Smirnov test was used to assess for normality. Mean and standard deviation of age and height by gender were compared using independent t-test. Mann-Whitney U-test was used to compare the weight by gender. For the data on postural sway, repeated measures analysis of variance (ANOVA) was used to examine the differences of the postural sway among the balance tasks and Bonferroni test was used to test for significant differences. For the EEG data, the Friedman test was used to examine the differences of the power of the brain waves among the eight balance tasks, and the Wilcoxon signed ranks test was used to assess for significant differences. The results were considered significant at $p < 0.05$.

Results

EEG Power of Alpha Wave Band

The relative difficulty of the balance tasks based on the postural sway has been previously published.[22] Figure 5 showed the raw EEG data and EEG of individual wave bands at POz during the least difficult task and the most difficult task. Relative to the control task, EEG power of all wave bands was greater in all the other tasks. The average increase of Alpha band power ranged from 4-22% at POz, 2-18% at Cz and, 3-20% at Fz. These changes were not significant relative to the control task (Figure 6).

EEG Power of Beta Wave Band

The average increase of Beta band power ranged from 3-22% at POz and Cz and, 2-18% at Fz. There were significant increases in Beta band power at POz ($p < 0.01$) and Cz ($p = 0.02$) relative to the control task (Figure 7). When eyes were closed in FACE-FIRM, Beta power increased by 17% and 16% at POz ($p = 0.03$) and Cz ($p = 0.04$) respectively. When the base of support was altered to tandem standing in TEO-FIRM, Beta power increased by 22% at POz ($p < 0.01$) and 21% at Cz ($p = 0.02$). When surface compliance was altered to foam in FAEO-FOAM, Beta power increased by 21% at POz ($p = 0.02$) and 22% at Cz ($p = 0.01$). When both base of support and surface compliance were altered together relative to the control task in TEO-FOAM, Beta power increased by 8% and 9% at POz ($p = 0.02$) and Cz ($p = 0.03$) respectively. When all 3 factors (vision, base of support and surface compliance) were altered from the control tasks in TEC-FOAM, Beta power increased by 9% at POz ($p = 0.02$) and 8% at Cz ($p = 0.01$).

EEG Power of Sigma Wave Band

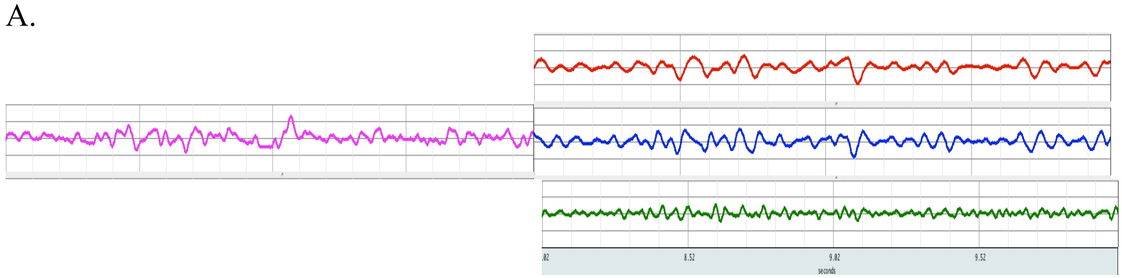
The average increase of the Sigma band power ranged from 11-36% at POz, 9-32% at Cz and 4-26% at Fz. There were significant increases in sigma band power at POz ($p < 0.001$) and Cz ($p = 0.01$) relative to the control task (Figure 8). When base of support was altered to tandem standing in TEO-FIRM, the sigma power increased by 36% at POz ($p < 0.01$) and 32% at Cz ($p < 0.01$). When surface compliance was changed to foam in FAEO-FOAM, the sigma power increased by 34% and 32% at POz ($p < 0.01$) and Cz ($p < 0.01$) respectively. When both base of support and surface compliance were altered relative to the control task in TEO-FOAM, sigma power increased by 21% at POz ($p < 0.01$) and 18% at Cz ($p < 0.01$). When all these factors (vision, base of support and surface compliance) were altered from the control tasks in TEC-FOAM, sigma power increased by 27% at POz ($p < 0.01$) and 21% at Cz ($p < 0.01$).

EEG Power Response to the Tasks Difficulty

The result of the postural sway ranked in order of task difficulty has been reported in a previous study [22]. The distribution of the power of all the wave bands at POz, Cz and Fz in response to the increasing order of task difficulty was similar (Figure 9-11). The power of all the wave bands increased in all the balance tasks when compared to the control tasks but only beta and sigma power showed significant increases at the central (Cz) and parietal area (POz) of the brain relative to the control tasks when eyes were opened in the tasks. The power of the bands decreased as the tasks became more difficult with vision and somatosensory information altered. When the balance task became more challenging with vision, base of support and surface compliance altered, the power of beta and sigma increased significantly again.

Raw EEG EEG of individual wave band

A.



B.

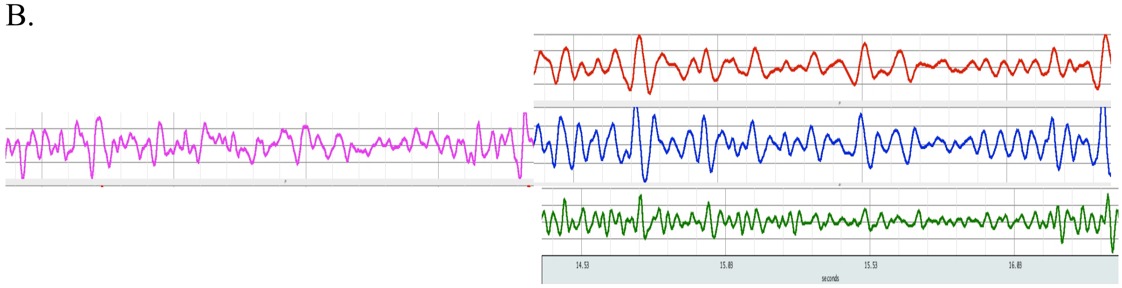


Figure 5. EEG activity at POz during the least difficult balance task, FAEO-FIRM (A) and the most difficult balance task, TEC-FOAM (B). Raw EEGs are shown on the left side of the Figure and EEGs of individual wave bands (alpha, beta and sigma) are shown on the right side of the Figure.

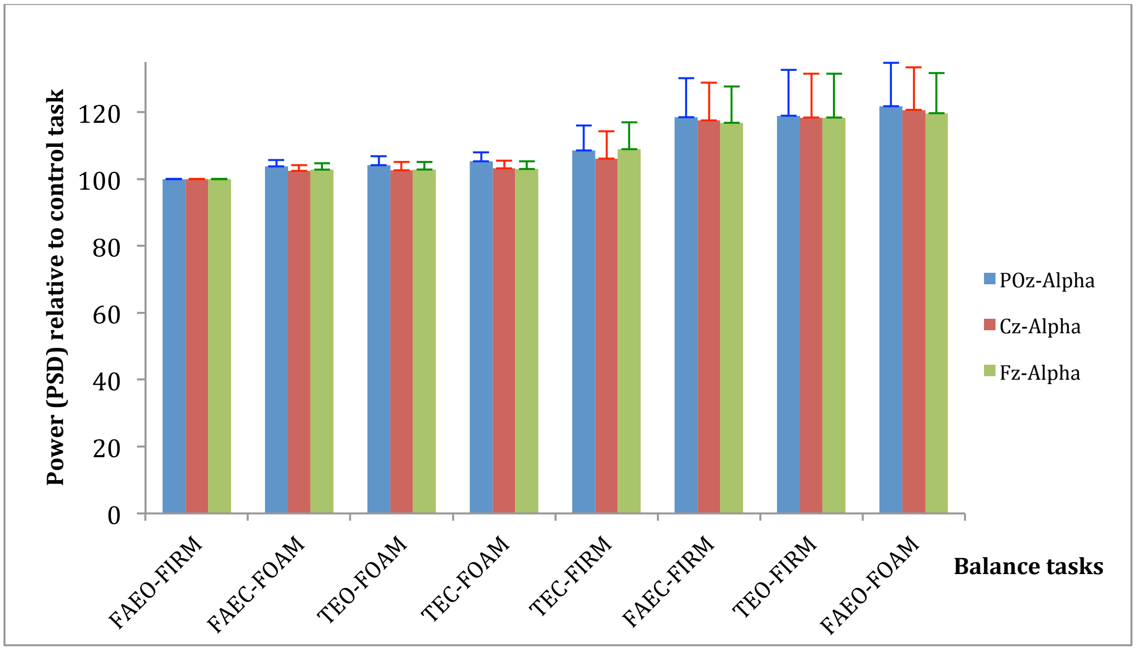


Figure 6. Mean ± SEM of the power (PSD) of Alpha band in the balance tasks relative to the control task at different EEG sites.

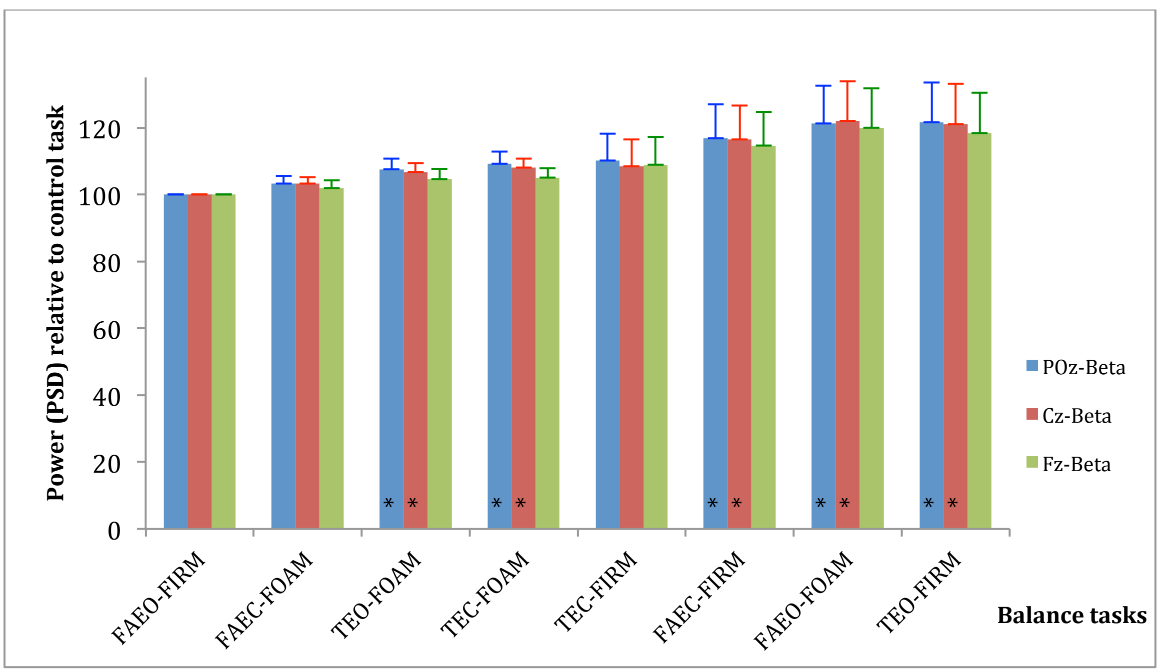


Figure 7. Mean ± SEM of the power (PSD) of Beta band in the balance tasks relative to the control task at different EEG sites. * $p < 0.05$.

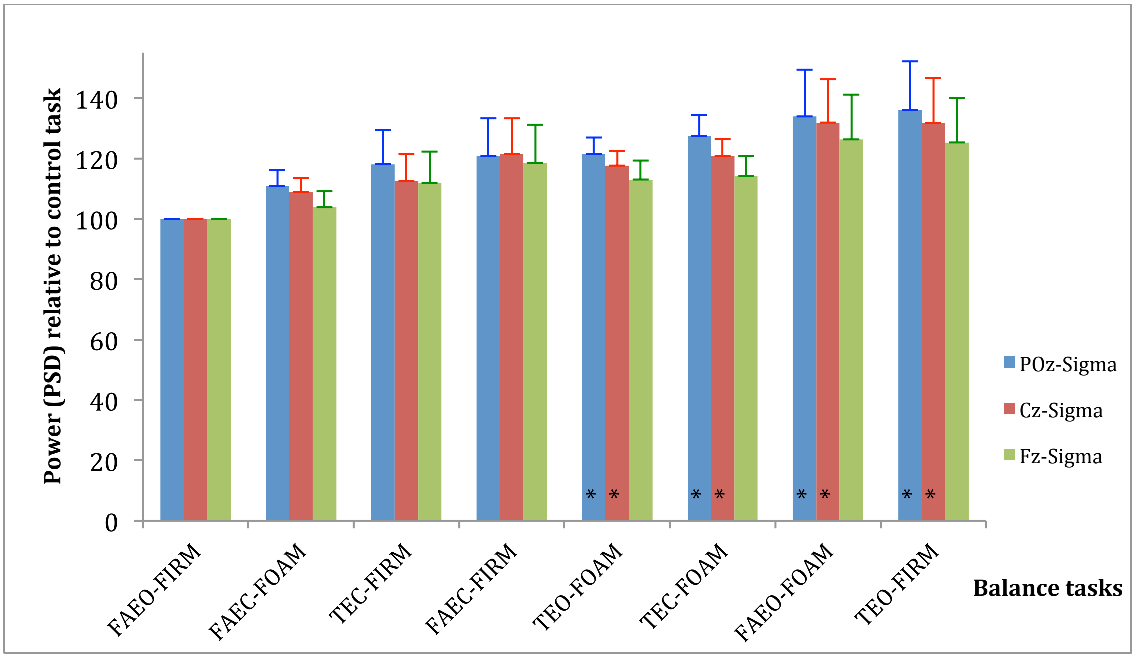


Figure 8. Mean ± SEM of the power (PSD) of Sigma band in the balance tasks relative to the control task at different EEG sites. * $p < 0.05$.

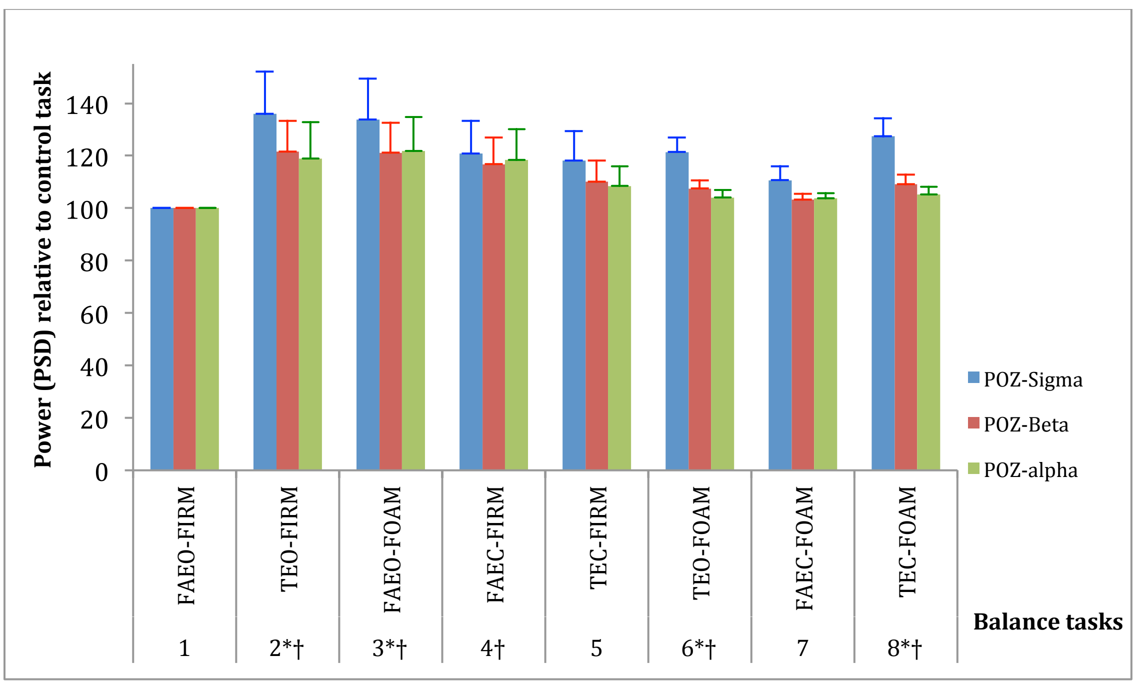


Figure 9. Mean ± SEM of the power of all wave bands in the order of the balance task difficulty at POz. * $p < 0.05$ for sigma wave. † $p < 0.05$ for beta wave.

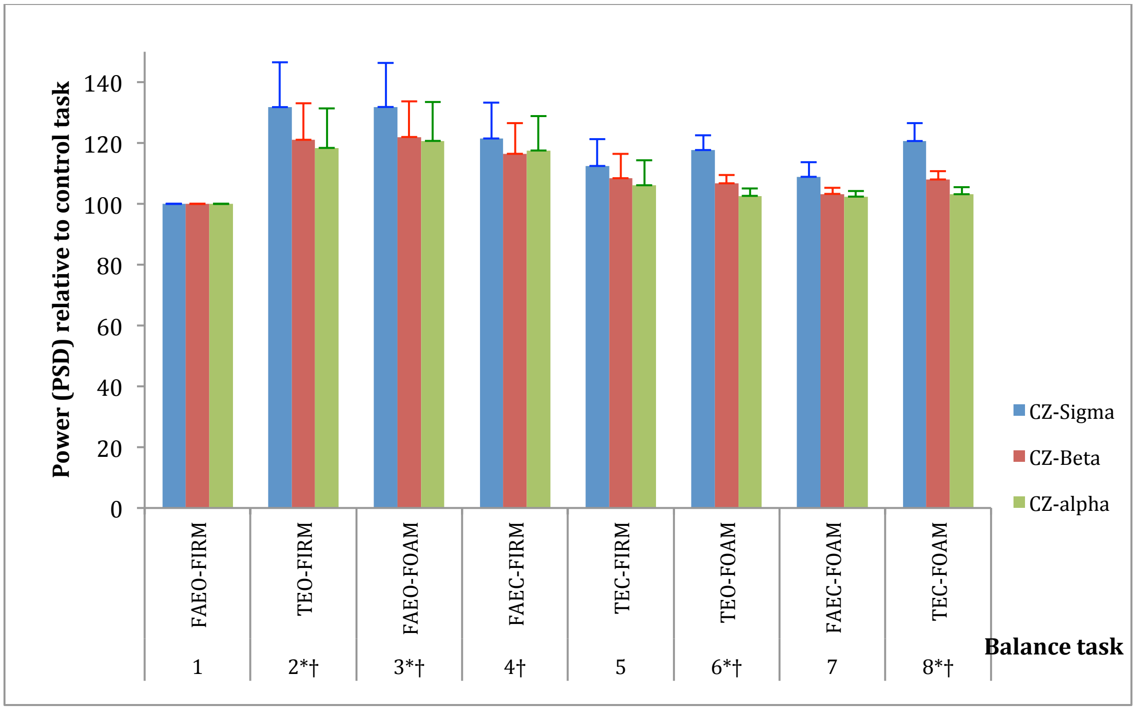


Figure 10. Mean ± SEM of the power of all wave bands in the order of the balance task difficulty at Cz. * $p < 0.05$ for sigma wave. † $p < 0.05$ for beta wave.

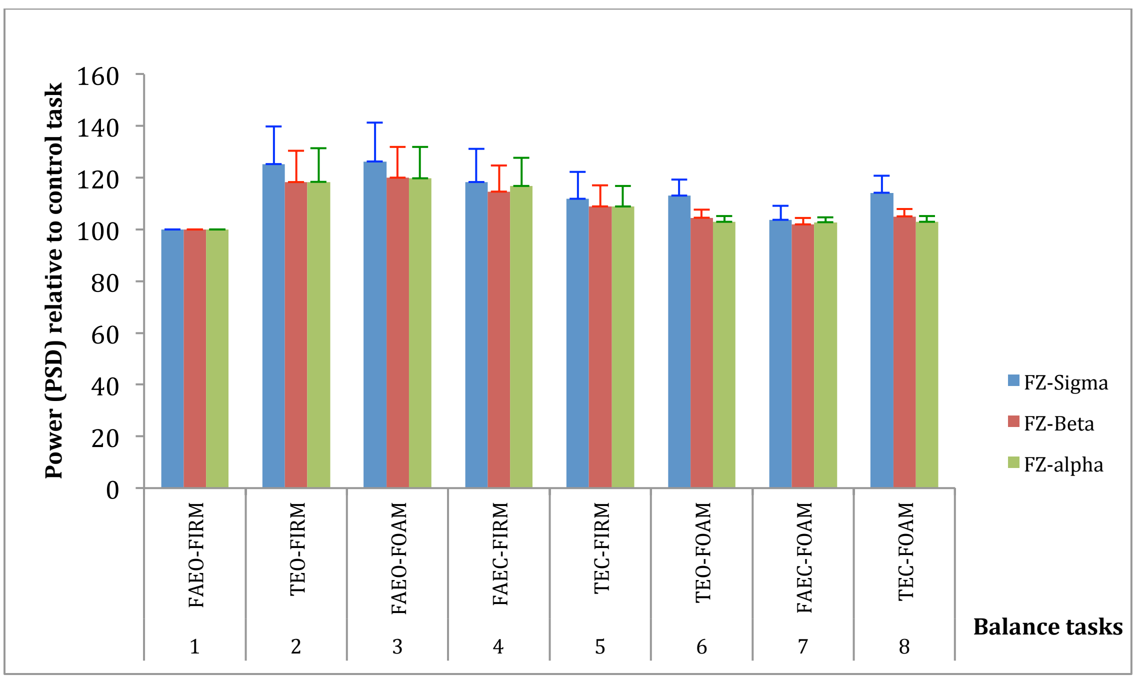


Figure 11. Mean ± SEM of the power of all wave bands in the order of the balance task difficulty at Fz.

Discussion

Effective balance training challenges sensorimotor integration and induces adaptation in the central nervous system. However, little is known about the cortical response to static balance exercises routinely used in sensorimotor training. This study assessed the changes in the EEG as related to different levels of task difficulty.

The distribution of the PSD for alpha, beta and sigma in response to the change of task difficulty was similar. EEG power of alpha, beta and sigma wave bands increased in all the tasks when compared to the control task but only beta and sigma power showed significant increases at the central (Cz) and parietal area (POz) of the brain relative to the control tasks when eyes were opened in the tasks. The cortical involvement decreased as the tasks became more difficult with vision and somatosensory information altered. When the task became more challenging with three sensory factors altered, the power of beta and sigma increased significantly, again.

Our results provide evidence that there was an increase in cortical activity during the commonly used static balance tasks relative to the control task. Soto and colleagues have reported the presence of cortical excitability during normal unperturbed quiet standing.[23] Other studies have indicated the increased corticospinal excitability during unstable stance.[24,25] Barry and colleagues also provided evidence for the cortical processing with visual input.[26] Although Slobounov and colleagues used a different EEG analysis technique, they also reported cortical activity preceding and accompanying the postural movements.[8]

Our results showed that the power of beta and sigma bands was higher when eyes were opened even with one or two sensory factor (base of support or surface compliance) altered. This may be due to processing of visual information available since the eyes were open. This finding concurs with a previous study showing that there is increased activation in the parietal area with visual demand.[27] One study has shown that the central nervous system is able to re-weight the sensory information based on the sensory context.[28] It is possible that our normal subjects with no impairment in their sensory systems, were able to re-weight the dependence from the somatosensory system to the visual input for balance and consequently postural sway was not significantly affected.

When the tasks became more difficult or with vision and somatosensory information altered, the postural sway increased but the EEG band power decreased relative to the less difficult tasks. Studies have shown that H-reflexes diminished when eyes were closed suggesting that there was an increase in the supraspinal excitability in the postural control when vision was compromised.[29,30] In our study, the reduced power in the EEG with eyes closed may due to a shift of the postural control from the cortex to the subcortical structures. These findings are consistent with previous studies suggesting the importance of subcortical structure in the postural control,[31,32] and an increase in the subcortical activity when postural demand increases[3].

During the most difficult task with vision, base of support and surface compliance altered, postural sway became the highest among all the tasks, but the band power of beta and sigma increased significantly at the central and parietal area of the brain relative to the control task. Although there may have been an increase in the subcortical activity as the tasks became more difficult, the increase in the EEG power in the most difficult task suggests that increased cortical activity was required in the more challenging tasks. Previous studies have suggested that cerebral cortex contributes to the postural control by sensorimotor processing of postural instability[8,9] or modification of postural responses through cortical response loops[5,33]. In addition, Teasdale and colleagues have also reported that more cognitive processing was required when the postural task became more difficult[34]. It is possible when balance task becomes more challenging with both visual and somatosensory information altered, the demand for cortical processing increases.

In our study, young healthy subjects were recruited; the result should not be extrapolated to other populations. Studies on older adults or patient populations are recommended. Also, this may be of special interest in individuals with diabetes when neuropathies are known. Furthermore, our sample size is small; a larger sample size is suggested in future studies. Future research is also recommended to examine the EEG power change of each wave band with balance training.

Conclusions

The results of this study provide evidence that there were increases in cortical activity during balance training tasks. EEG power of beta and sigma wave bands showed significant increases at the central (Cz) and parietal (POz) area of the brain relative to the control tasks when eyes were opened in the tasks. The cortical involvement decreased as the tasks became more difficult with vision and somatosensory information altered. When the task became more challenging with vision, base of support and surface compliance altered, the power of beta and sigma increased significantly again. The results suggest that there was increased subcortical control with increased task difficulty, however; further research is required to elaborate this possibility.

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CHAPTER FOUR

DISCUSSION

Falls are the leading cause of death in the elderly (CDC, 2009). Balance exercises are known to restore postural control and to reduce the risk of falling (Madureira et al., 2007, Gillespie et al., 2009b). Balance exercises have shown to be beneficial in a variety of populations, nevertheless, the exercises used in the balance program are very diverse and little is known about cortical involvement and the muscle activities of the lower extremity during common balance tasks used in balance training. In addition, there is no scientific guideline on the progression of balance exercises based on the difficulty of the balance tasks. This study examined the postural sway, the cortical response and the muscle activation of the hip and ankle muscles during eight common balance-training tasks. Balance exercises were ranked in the order of the difficulty based on the postural sway to provide evidence-based paradigm for the progression of balance program and to establish baseline data for future studies on the elderly and other populations.

The results of this study showed that postural sway, EEG power of the beta and sigma wave bands, and EMG activity of the hip and ankle muscles were significantly affected by the alteration of sensory information in the eight common balance tasks. The postural sway was affected by the extent of sensory information available for postural control. The recruitment of specific muscles was affected by the context of the tasks rather than the number of sensory factors altered. EEG power of beta and sigma wave bands showed significant increases at the central and parietal area of the brain relative to the control tasks when the eyes were open. The cortical involvement decreased as the task became more difficult with vision and somatosensory information altered. When the balance task became more challenging with three sensory factors altered, the cortical activity increased significantly again. Our results suggested that balance training should start with alteration of one sensory factor by first altering the somatosensory input (base of support then the surface compliance), and followed by excluding the visual input. The balance training should be progressed by altering two then three sensory factors. A balance program should include exercises to strengthen hip and ankle muscles to facilitate the postural control in static balance tasks.

Our study showed that postural sway and cortical activity were affected by the sensory information available for postural control (Figure 12). When the eyes were opened with one sensory factor (base of support or surface compliance) altered, significantly more cortical activity was observed. This is probably due to the processing of visual information available since eyes were open. This finding concurs with a previous study showing that an increased activation in the parietal area with visual demand (Mizelle et al., 2010). Previous research has shown that the central nervous system is able to "re-weight" the sensory information based on the sensory context (Peterka, 2002). It is possible that our normal subjects with no impairment in their sensory systems, were able to re-weight the dependence from the somatosensory system to the visual input for balance and consequently postural sway was not significantly affected.

When 2 sensory factors (vision and somatosensory inputs) were altered, the tasks became more difficult with higher postural sway but the power of EEG band decreased relative to the less difficult tasks. It may due to the reduced sensory information available for cortical processing and consequently, the postural sway increased accordingly. It is possible when sensory information becomes less available, postural control is shifted from the cortex area to the subcortical structures. Previous studies have suggested the importance of subcortical structure in the postural control (Doyon et al., 1997, Prentice and Drew, 2001). Ouchi also demonstrated that the subcortical activity increased when postural demand increased (Ouchi et al., 1999).

When 3 factors were altered, the postural sway became the highest among all the tasks, the power of the EEG bands increased significantly again even with minimum sensory information available. Teasdale and colleagues have reported that many cognitive resources were required in postural control and more cognitive processing was required when the postural task became more difficult (Teasdale and Simoneau, 2001). It is possible when the balance task becomes more challenging with both visual and somatosensory information altered, the demand for cortical processing increases.

Although EMG activity of the hip and ankle was affected by the sensory input, the recruitment of specific muscles seems to depend on the context of the tasks rather than the numbers of sensory factors altered. The EMG activity of the hip muscles was significantly higher only in tasks with tandem standing regardless of the status of the vision and surface compliance. Previous studies have reported that the use of the hip strategy increased in standing with a narrow base of support (Amiridis et al., 2003, Gatev et al., 1999, Shumway-Cook and Horak, 1990, Horak and Nashner, 1986). On the other hand, the EMG activity of the ankle muscles showed a significant increase in all the tasks but was dominant in tasks with feet apart. This finding is in line with previous studies showing that ankle mechanism dominates normal quiet standing with feet apart (Gatev et al., 1999, Horak and Nashner, 1986, Shumway-Cook and Horak, 1990).

Our findings suggest that in the early stage of the balance training, only one sensory factor should be altered in the progression of the balance tasks. As balance improves, balance tasks should include the alteration of two sensory factors to challenge the postural stability. For an advanced balance challenge, three factors should be altered to increase the demand on the postural control. The following recommendations provide the guidelines in the progression of the balance training in an increasing order of difficulty. Specific balance tasks were included in the parentheses:

1. Start with the easiest task with vision (eyes open) and somatosensory (feet apart on firm surface) information present, (FAEO-FIRM).
2. Alter the somatosensory input by changing the base of support, (TEO-FIRM).
3. Alter the somatosensory input by changing the compliance of the supporting surface, (FAEO-FOAM).
4. Exclude the visual input by closing the eyes, (FAEC-FIRM).
5. Alter somatosensory (base of support) and visual (vision) inputs, (TEC-FIRM).
6. Alter 2 factors in somatosensory inputs (base of support and surface compliance), (TEO-FOAM).
7. Alter somatosensory (surface compliance) and visual inputs, (FAEC-FOAM).
8. Alter 3 factors (vision, base of support and surface compliance) in a task, (TEC-FOAM).

The data from the EMG study suggests the significance of hip and ankle muscle activities in tasks on foam and tasks with tandem standing. Therefore, to design an effective balance program, it is imperative to include strengthening exercises of gluteal maximus, gluteal medius, tibialis anterior and medial gastrocnemius to ensure the progression of the balance tasks.

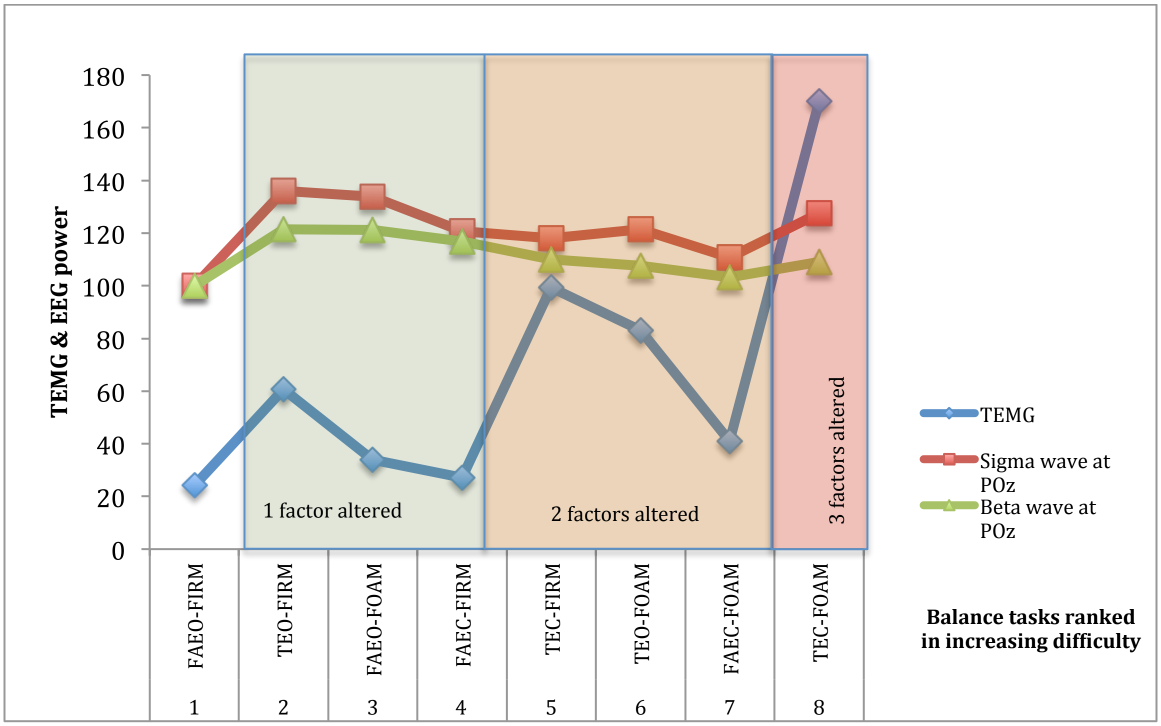

Figure 12. TEMG and EEG power of sigma and beta band at POz during eight balance tasks.

Limitations and Suggestions for Future Research

In our study, young healthy subjects were recruited; the results should not be extrapolated to other populations. Further studies on older adults or patients with diabetes are suggested. Furthermore, the sample size is small and a larger cohort is recommended in future studies. Future studies are needed to examine the changes in postural sway, muscle recruitment and EEG power with balance training.

CHAPTER FIVE

CONCLUSIONS

The results of this study showed that postural sway, EEG power of the beta and sigma wave bands, and EMG activity of the hip and ankle muscles were significantly higher due to the alteration of sensory information in the eight common balance tasks when compared to the control task. The postural sway was affected by the extent of sensory information available for postural control. The recruitment of specific muscles was affected by the context of the tasks rather than the number of sensory factors altered. EEG power of beta and sigma wave bands showed significant increases at the central and parietal area of the brain relative to the control tasks when the eyes were open in the task. The cortical involvement decreased as the task became more difficult with vision and somatosensory information altered. When the balance task became more challenging with vision, base of support and surface compliance altered, the power of beta and sigma increased significantly. Our results suggested that balance training should start with alteration of one sensory factor by first altering the somatosensory input (base of support then the surface compliance), and followed by excluding the visual input. The balance training should then be progressed by altering two then three sensory factors. A balance program should include exercises to strengthen hip and ankle muscles in order to facilitate the postural control in static balance tasks.

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APPENDIX A

DEMOGRAPHIC DATA FORM

POSTURAL SWAY, EEG & EMG ANALYSIS OF HIP & ANKLE MUSCLES DURING 8 BALANCE TRAINING TASKS

DEMOGRAPHIC DATA:

DATE: _______________

SUBJECT: _____________

SEX: ___________

AGE: ___________

HEIGHT: ____________cm

WEIGHT: ___________lb.

DOMINANT SIDE: ______________

Distance between ASIS: ____________________ cm

SEQUENCE OF BALANCE TASKS: _1__ ___ ___ ___ ___ ___ ___ ___

INCLUSION CRITERIA: Checked ☐

EXCLUSION CRITERIA: Checked ☐

INFORMED CONSENT: Signed ☐

APPENDEX B

INFORMED CONSENT FORM

LOMA LINDA UNIVERSITY

School of Allied Health Professions

Informed Consent to Participate in Research

"Cortical response & Motor changes with balance tasks"

PURPOSE AND PROCEDURES

You are invited to participate in a study to examine the responses of the brain to balance tasks. We are looking for young healthy subjects in the age range of 20-45 years old, free of any headache, migraine, diabetes mellitus, orthopedic conditions or neurological conditions, or uncorrected visual impairment that may affect their balance. You cannot be taking any medication or central nervous stimulants in the diet that may affect your balance. You cannot be participating in any balance exercises regularly.

When you come for the study, we will first obtain baseline demographic data from you and we will ask you to choose from a few envelopes to determine the sequence of the balance tasks you will be subjected to. Then we will place some small adhesive discs on the muscles of your dominant leg to measure the electrical activity in your muscles. We will have you lie down on a table and you will be asked to resist as hard as you can against manual resistance with your leg so we can record the maximum electrical activities of certain muscles on your leg.

Once you sit up, we will place nine adhesive discs on the surface of your entire head to measure the electrical activity of your brain. You will not need to shave your head or cut your hair for this procedure. We will then attach a small device called an accelerometer on the strap that is used to secure the adhesive discs on your head. It is a non-invasive device that will be placed at the back of your head over your hair. It is used for the measurement of position and direction of movement of your head. We will place some adhesive discs on the left side of your chest to measure the electrical activity of your heart. Next, we will put a gait belt around your waist as a safety measure. A licensed physical therapist will always be within arm-reach distance as a precaution. We will have you stand on a small platform.

Then you will be asked to keep your eyes fixed on a target on the wall, with arms crossed in front of your chest and stand with feet apart quietly for 6 seconds. Thereafter, you can rest in standing for 10 seconds while holding onto the support. We will have you repeat the same task 3 times. Then you will be placed in 7 other balance tasks, requiring you to stand with feet apart or in tandem position on firm surface or on foam, with eyes opened or closed.

The experiment will take place in Nichol Hall Room A640 at Loma Linda University and you will be required to come only one time for 2 hours.

_____________Initial

_____________Date

Loma Linda University
Adventist Health Sciences Center
Institutional Review Board
Approved 7/11/11 Void after 5/24/2012
5110123 Chair R L Ragelyom

RISKS

You may lose your balance while performing the balance tasks in the procedure. A trained physical therapist will be near you to keep you from falling. You may have skin irritation at the leg, left side of your chest wall or on the surface of your skull where the adhesive discs are placed. The Institutional Review Board of Loma Linda University has determined the risks for this study are minimal.

BENEFITS

There are no benefits to you personally. The study may provide a better understanding of the brain response to balance exercises. It may provide objective evidence of the best way to improve balance.

PARTICIPANTS RIGHTS

Participation is voluntary. You may leave the study at any time. If at any time during a procedure you experience tiredness or discomfort beyond what you are willing to endure, just tell the person conducting the procedure you want to stop. This decision will NOT affect your standing with those conducting the study or loss of benefits that you are entitled to.

CONFIDENTIALITY

All records will be confidential. No information that could identify you personally will be recorded in the research data. Any publication resulting from this study will refer to you by ID number and not by your name.

COSTS/COMPENSATION

There is no cost for participating in these studies; you will receive monetary compensation of $50 for participation.

IMPARTIAL THIRD PARTY

If you wish to contact a third party not associated with the study for any questions or a complaint, you may contact the Office of Patient Relations at Loma Linda University, Loma Linda University Medical Center, Loma Linda, California 92354. Phone (909) 558-4647.

____________Initial

____________Date

Loma Linda University
Adventist Health Sciences Center
Institutional Review Board
Approved 7/11/11 Void after 5/24/2012
5110123 Chair

“Cortical response & Motor changes with balance tasks”

INFORMED CONSENT STATEMENT

I have read the contents of the consent form and have listened to the verbal explanation given by the investigator. My questions regarding the study have been answered to my satisfaction. I hereby give voluntary consent to participate in the study described here. Signing this form does not waive my rights nor does it release the responsibilities of the principal investigator, Jerrold Petrofsky Ph. D. or Loma Linda University of their responsibilities. I may call Dr. Jerrold Petrofsky during routine office hours at (909) 558 4300 ex 82186 or leave a voice mail message at this number during non-office hours.

_________________ ______

Signature of subject Date

INVESTIGATOR'S STATEMENT

I have reviewed the contents of the consent form with the person signing above. I have explained potential risks and benefits of the study.

Signature of investigator __________________

Phone Number ________________ Date _______________

Loma Linda University
Adventist Health Sciences Center
Institutional Review Board
Approved 7/11/11 Void after 5/24/2012
5110123 Chair