THE EFFECTS OF VIBRATORY NOISE ON RESPONSES TO POSTURAL STABILITY

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Lois A. Lanaria
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Thesis Approval(s):

Kurosh K. Darvish, Ph. D., Thesis Advisor, Department of Mechanical Engineering

Emily A. Keshner, PT, EdD, Department of Physical Therapy

Richard T. Lauer, Ph. D., Department of Physical Therapy

ABSTRACT

Our human balance system is critical for preventing falls. The system consists of a complex set of sensorimotor controls that includes integration of sensory inputs including sight, touch and vestibular to produce motor output. Tactile afferents from the plantar surface contribute to the human balance and movement control system. Loss of sensory information could lead to impaired balance primarily because of impaired detection of changes in upright position, delayed postural reflexes, or failure to realize how far one's center of mass has been displaced thus increasing the probability of falls.

Somatosensory and visual information must be integrated to interpret complex sensory environment. Sensory pathways that are simultaneously feeding inputs into the system exhibit non-linear behavior and it is unlikely that the role of a single pathway can be characterized in a static environment. As the sensory environment changes, the need to re-weight the relative dependence on each senses is essential for maintaining stability. Thus, attention also plays an important role in postural control. Attention can be defined as the individual's capacity for information processing. Performing two or more tasks at the same time may require more than an individual's attention capacity and thereby may weaken performance in the other task.

Stochastic resonance phenomena has been shown to enhance sensory information processing and perception. This series of studies sought to analyze the effects of vibrotactile noise on human postural responses using a sub-threshold vibration (SV) and above-threshold vibration (AV). The vibrotactile noise was applied at the soles of both feet with six DC vibrator disks embedded in open-type footwear. Twenty one healthy adults wearing the vibrating footwear stood quietly on a compliant surface for 90 seconds inside a three-wall virtual environment. The visual conditions were either eyes closed, eyes open or a continuous visual flow field in a pitch-up direction at constant velocity of 30°/sec. A dual task paradigm was presented as a computation task, the Fibonacci sequence. The first 30 seconds of the 90 seconds trial had no vibration followed by 30 seconds of either sub-threshold or above-threshold vibration. Vibration was removed for the final 30 seconds. Root mean squares (RMS) and approximate entropy (ApEn) of center of mass (COM) and center of pressure (COP) excursions were calculated in the anterior-posterior (AP) and medio-lateral (ML) directions for each 30 second time period and normalized to each subject's initial position. Approximate entropy (ApEn) was used to detect movement variability in a time series to determine the unpredictability of the postural responses. COP and COM data were tested for statistical significance using repeated measures analysis of variance (ANOVA) with within-subject factors of vision (3 levels: eyes closed, eyes open and pitch-up), task (2 levels: single task and dual task), and vibration level (2 levels: sub-threshold vibration and above-threshold vibration) at a 95% confidence level ($p<0.05$).

Results supported the hypothesis that the application of SV and AV affected COP regularity and variability differently when subjected to different visual conditions (eyes closed, eyes open and pitch-up). COM randomness increased (higher ApEn) when attention was diverted from postural control which is in agreement with previous studies. The decrease in COM AP randomness (lower ApEn) with vibration suggested that the

application of vibration increased the amount of attention invested in postural control or balance when performing an attention demanding cognitive task. The SV increased the COP-AP regularity (lower ApEn) during eyes-closed and eyes-open conditions while AV increased COP-AP variability (increased RMS) during the pitch-up visual condition.

In conclusion, posture and balance were affected by the application of vibration noise. The vibration noise enhanced the amount of attention invested in postural control while performing an attention demanding cognitive task and sensory-motor learning was achieved by increasing COM sway structure regularity (lower ApEn) but not the sway magnitude. These results suggest that the interaction between vibration noise and an attention demanding task resulted in the temporal re-structuring of the postural control system without affecting the equilibrium region for the COM sway excursion. Vibration noise appears to facilitate postural control by altering postural response regularity (lower ApEn). For COM, only postural response regularity but not sway variability was affected by vibration noise in relation to vision regardless of the vibration level (SV or AV). For COP postural responses, the effect of SV and AV differs. Due to the perception of self-motion from the pitch-up visual condition, COP postural response most likely arise from cortical level. Since AV only affected COP responses during pitch-up visual condition and not SV, this study suggests that AV applied affected the cortical level of postural control. Effects of SV on postural responses between the eyes-open and eyes-closed vision conditions suggests that SV may affect a subcortical level of postural control. Understanding the effects and mechanism of vibratory noise may help in the design of effective interventions to prevent falls and rehabilitation. These results provide the scientific basis for development of a SR-based rehabilitation device for people with sensory information and processing deficiency as occurs with aging or stroke. The finding of after effects of vibratory noise can be used to determine dosage of vibrotactile stimulation in the design of vibrating footwear.

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CHAPTER 1

INTRODUCTION

In elderly, increased vibrotactile threshold could lead to an inability to detect changes in upright position (Hijmans et al., 2007; Wells, Ward, Chua, & Timothy Inglis, 2005), or delayed postural reflexes regulated by the plantar pressure under the foot as sensed by cutaneous mechanoreceptors in the sole of the foot (Wu & Chiang, 1996). Age-related impairment in plantar vibration sensation may lead to falls, a major cause of accidental death in elderly (Galica, 2009; Priplata et. al., 2006; Wells, 2005).

The somatosensory system plays an important role in postural control. One of its subsystems is the tactile system. The skin is the primary organ of the tactile system that contains receptors. The cutaneous receptors on the plantar surface of the foot provide afferent information to the central nervous system (CNS).The foot plantar surface receptors (mechanoreceptors) have been shown to contribute its role in standing balance and movement control (Kavounoudias, Roll, & Roll, 1998; Kennedy & Inglis, 2002; Magnusson, Enbom, Johansson, & Pyykko, 1990; Roll, Kavounoudias, & Roll, 2002). Various studies have shown that tactile information influences postural stabilization (Diener, Dichgans, Guschlbauer, & Mau, 1984; Meyer, Oddsson, & De Luca, 2004a; Meyer, Oddsson, & De Luca, 2004b). Maurer *et al.* suggested that cutaneous signals play a role in determining body orientation in space and specifying the support on which feet are resting (Maurer, Mergner, Bolha, & Hlavacka, 2001). It was also suggested that plantar cutaneous receptors are involved in the recovery and maintenance of balance and posture due to their anatomical location where it interfaces between the body and the support surface (Thompson, 2011). Tactile stimuli, detected by the cutaneous mechanoreceptors (Meissner's corpuscles, Pacinian corpuscles, Merkel's disks and Ruffini endings) provide the CNS with information about spatial distribution of stimulation that is translated into a body position indicating the direction and amplitude of the body inclination (Hijmans, Geertzen, Dijkstra, & Postema, 2007; Kavounoudias et al., 1998). The mechanoreceptors are able to sense the vertical and horizontal components of ground reaction forces. Ruffini and Meissner mechanoreceptors are slowly and moderately fast adapting mechanoreceptors making it ideal for tranducing the normal component of the ground reaction which is slowly changing around a large average value. On the otherhand, the Pacinian corpuscles which are fast adapting and have large receptive field are ideal for the horizontal component oscillated more rapidly around zero (Morasso, Baratto, Capra, & Spada, 1999).

Vibrotactile detection threshold will increase with age (Kenshalo, 1986; Liu et al., 2002; Verrillo, 1980). Changes in skin mechanics affects the transmission of vibration through the skin mechanoreceptors thus resulting in changes in vibration sensitivity. Decreased sensitivity could be due to the reduction in the number of mechanoreceptors under a given contact area or due to structural changes within the receptors that occurs with age. Another possible reason for decreased sensitivity in elderly is contributed by age-related changes in myelination that results in slowed nerve conduction velocity. Slowed conduction velocities of compound action potentials in the large primary afferents would induce vibrotactile sense dysfunction and higher threshold (Kenshalo, 1986; Wells, Ward, Chua, & Inglis, 2003).

The vision system provides an important sensory information in postural control and balance. Increased responsiveness in visual sensory information suggests the shift of reliance in the vision system (Keshner, Kenyon, & Langston, 2004; Streepey, Kenyon, &

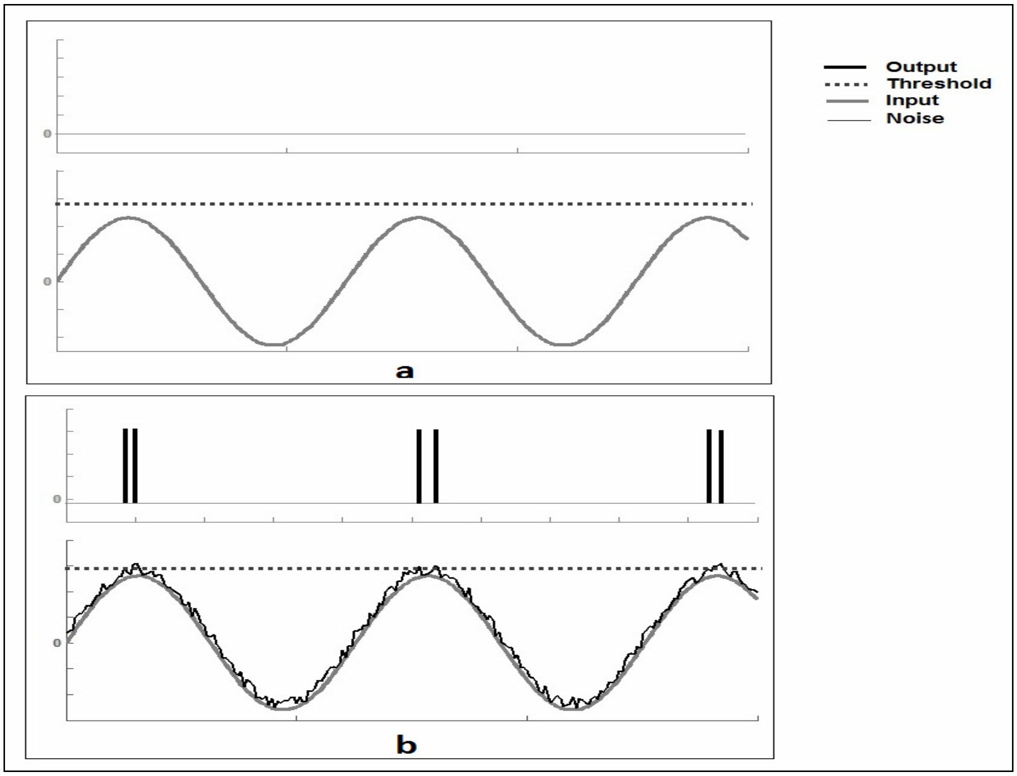
Keshner, 2007). Somatosensory and visual system sensory information must be integrated to interpret complex sensory environment. As the sensory environment changes the need to re-weight the relative dependence on each senses is essential for maintaining stability (Horak, 2006). Sensory pathways that are simultaneously feeding inputs into the system exhibits a non-linear behavior and is unlikely that the role of a single pathway can be characterized in a static environment (Keshner et al., 2004).

Aside from the sensory information from visual, vestibular, and somatosensory systems, attention also plays an important role in postural control. Attention can be defined as the individual's capacity of information processing (Woollacott & Shumway-Cook, 2002). Performing two or more tasks at the same time may require more than an individual's attention capacity and thereby may weaken the performance of the other task. To study attention and postural control, a dual task paradigm was conducted to examine the effects of the vibration on postural control while performing an attention demanding cognitive task. Cognitive functioning and control of posture and balance are related to some extent (Andersson, Hagman, Talianzadeh, Svedberg, & Larsen, 2003). Postural control has been observed to involve either automation, cognition, or both. Dual task paradigms have been found to impair posture control due to the divided allocation of attention.

Studies have shown that the addition of noise in a system can enhance the detection and transmission of weak somatosensory signals through a mechanism known as stochastic resonance (SR) (Khaodhiar et al., 2003; Priplata et al., 2006; Wells et al., 2005). Stochastic resonance is a phenomenon wherein the a nonlinear system response is optimized by the presence of a weak periodic and aperiodic nonzero noise input signal (Benzi, Sutera, & Vulpiani, 1981; Collins, Imhoff, & Grigg, 1996). Noise is defined as any unwanted activity or random fluctuation to the signal. Noise is normally known to interfere with signal detection and system performance, but several studies have shown that the addition of noise to a sub-threshold signal makes the signal detectable (Priplata et al., 2006; Wells et al., 2005). Collins et. al. (1996) demonstrated aperiodic stochastic resonance experimentally in mammalian cutaneous mechanoreceptors. The receptors were subjected to a peri-threshold input stimulus plus noise. The presence of a nonzero level of noise to cutaneous mechanoreceptors in mammals optimized the ability to detect weak broadband stimulus (Collins et al., 1996).

There are three fundamental components of SR: (1) a detection threshold which is the minimum amount of signal needed to detect an event or activity, (2) a subthreshold input signal which is the stimulus in the environment that is to be detected, and (3) a mechanical or electrical noise, a spontaneous signal that is uncorrelated with the target signal (Gingl, Kiss, & Moss, 1995; Wells et al., 2005). For people with high vibrotactile threshold, a much greater amplitude is needed to generate impulses in the associated nerve. If the input signal does not reach the detection threshold then the nerve does not generate an output (Figure 1-1a) thus no sensation is felt. But when adequate amount of noise is added to the input signal, the signal and noise reaches or exceeds the detection threshold and produces an output signal (Figure 1-1b) thus increasing the vibrotactile sensitivity. Several studies were able to demonstrate the SR behavior where the application of noise lowers vibrotactile threshold thus increasing vibrotactile sensitivity (Khaodhiar et al., 2003; Liu et al., 2002; Priplata et al., 2006; Wells et al., 2005) and ameliorating age-related impairments in balance control (Priplata, Niemi, Harry, Lipsitz, & Collins, 2003). The goal of these studies is to analyze the movement behavior that will allow us to study the effects and mechanism of the vibratory noise stimulus on the human balance system.

Figure 1-1: Illustration of stochastic resonance. (a) The input signal is below the threshold level thus it did not produce any output. (b) The input signal added with noise produces an output when the input signal plus noise crosses the threshold level.



The control of posture is a complex system and there is a possibility that biomechanical measures of postural sway may not be capable of detecting subtle changes in postural control. Measures such as approximate entropy applied to biological signals are expected to reflect the state of the biological system (Borg & Laxaback, 2010; Harbourne & Stergiou, 2009). Approximate entropy (ApEn) which is a regularity statistic developed from nonlinear dynamics can be used to quantify the regularity or predictability in a time series (Cavanaugh et al., 2005; Cavanaugh et al., 2006; Dusing, Kyvelidou, Mercer, & Stergiou, 2009) or a measure of the system's complexity (Haran & Keshner, 2008; Stergiou, Harbourne, & Cavanaugh, 2006).

During dual task performance, entropy changes were found to be independent of the amplitude in COP oscillations (Cavanaugh, Mercer, & Stergiou, 2007). A decrease in entropy may be interpreted as an increase in the amount of attention invested in postural control or balance thereby increasing the regularity of the COP trajectories (Cavanaugh et al., 2007; Donker, Roerdink, Greven, & Beek, 2007). Conversely, higher entropy suggests that balance requires less attention or increased automaticity (Stins, Michielsen, Roerdink, & Beek, 2009). ApEn was used to quantify changes in postural responses. Therefore, the analysis in postural responses using ApEn which measures the sway oscillation's regularity or randomness maybe a valuable supplemental tool for measuring subtle changes in postural response.

1.1 Statement of the Problem

The vision system is primarily involved in postural and balance control. Previous studies have shown an increase in responsiveness to visual information suggests the shift of reliance in visual information. Most studies examining the effect of vision on postural responses to a vibration on plantar foot surface have investigated the effects of the visual inputs only with earth-fixed or eyes-closed. Aside from visual feedback, attention also plays an important role in postural control. The level of allocation of attention in postural control with the application of vibration was inferred in the preliminary study conducted. The result of the preliminary study suggests that vibration contributed to the reallocation of attention in postural control and the different levels (sub-threshold and above-threshold) of vibration may have affected postural control differently. To better understand how posture and balance can be affected by vibration noise at the sole of the foot to facilitate postural stability and control in relation to vision and level of attention, a visual environment that will immerse the subject in visual flow and a dual task paradigm has been used in this study.

1.2 Objectives

The objective of this research was to investigate and analyze the effects and underlying mechanism of the vibratory noise stimuli to postural control and balance. The goal is to understand whether sub-threshold vibration noise at the sole of the foot facilitates postural control with simultaneous demands from vision and level of attention. We will employ ApEn analysis to test the hypothesis on the role of attention in postural control with levels of vibration and the validity of quantifying the role of attention using ApEn. Understanding the effects and mechanism of vibratory noise may help in the design of effective interventions to prevent falls and rehabilitation.

1.3 Hypotheses

The purpose of these experiments is to determine how adding sub-threshold and above-threshold vibration at the sole of the foot affects postural control with increased demands to attention. If we manipulate the sensory information at the plantar foot surface, we may be able to distinguish between the somatosensory and visual dynamics controlling balance. Effective rehabilitation of posture and balance to improve mobility and to prevent falls requires a better understanding of the multiple mechanisms underlying postural control. This study hypothesized that:

(1) If different levels of vibration noise is applied with a dual attention demanding task, then it will affect postural response with sub-threshold vibration increasing

regularity of the postural response and above-threshold vibration increasing variability of the postural response.

(2) If we apply sub-threshold and above-threshold vibration noise during challenging visual flow, then sub-threshold vibration will affect postural response by increasing sway regularity and above-threshold vibration will affect postural response by increasing sway variability.

CHAPTER 2

REVIEW OF RELATED LITERATURE

2.1 The Role of Tactile System in Posture and Balance

The control of posture and balance involves the integration of sensory information from the visual, vestibular, and somatosensory systems (Horak, 2006; Hughes, Duncan, Rose, Chandler, & Studenski, 1996; Oie, Kiemel, & Jeka, 2002; Peterka, 2002; Vuillerme & Pinsault, 2007). During upright stance, the somatosensory system provides a significant sensory input and feedback to control balance (Fitzpatrick, Rogers, & Mccloskey, 1994; Maurer, Mergner, & Peterka, 2006). The somatosensory system can be divided into two categories; the proprioception and the tactile system. When a person is standing, the mechanoreceptors on the feet have been shown to provide significant sensory input (Bernard-Demanze, Vuillerme, Ferry, & Berger, 2009; Chiang & Wu, 1997; Kavounoudias, Roll, & Roll, 1998; Magnusson, Enbom, Johansson, & Pyykko, 1990; Maurer, Mergner, Bolha, & Hlavacka, 2001; Meyer, Oddsson, & De Luca, 2004; Roll, Kavounoudias, & Roll, 2002; Stal, Fransson, Magnusson, & Karlberg, 2003; Toledo & Barela, 2010). The cutaneous mechanoreceptors on the plantar surface of the foot provide sensory afferent information to the CNS. The mechanoreceptors are able to sense the vertical and horizontal components of the ground reaction forces. Tactile stimuli, detected by the cutaneous mechanoreceptors (Meissner's corpuscles, Pacinian corpuscles, Merkel's disks and Ruffini endings) provides the CNS with information about spatial distribution of stimulation that is translated into a body position indicating the direction and amplitude of the body inclination (J. M. Hijmans, Geertzen, Dijkstra, & Postema, 2007; Kavounoudias et al., 1998). Studies that investigated the role of the tactile system on postural control used either feet anaesthesia (Fitzpatrick et al., 1994; Meyer et al., 2004; Perry, McIlroy, & Maki, 2000; Stal et al., 2003), change in support surface property (Chiang & Wu, 1997; Fransson, Gomez, Patel, & Johansson, 2007; Patel, Fransson, Lush, & Gomez, 2008), plantar vibration stimulation (J. M. Hijmans, Geertzen, Zijlstra, Hof, & Postema, 2008; Kavounoudias, Roll, & Roll, 2001; Khaodhiar et al., 2003; Roll et al., 2002; Siedentopf et al., 2008), or subjects that have diabetic neuropathy or stroke (J. M. Hijmans et al., 2008; Khaodhiar et al., 2003; Priplata et al., 2006). Changing the support surface property like standing in a foam surface causes disruption in the sensory information at the point of contact with the surface (Patel et al., 2008) thus changing the plantar pressure (Chiang & Wu, 1997) and increasing movement in the lower body segments (Fransson et al., 2007). When the feet were anaesthesized, effects on stability were found to be smaller but significant (Fitzpatrick et al., 1994) with eyes closed in unperturbed stance (Meyer et al., 2004) and in rapid compensatory stepping reactions provoked by unpredictable perturbation (Perry et al., 2000). Hypothermic anaesthesia caused reduced sensitivity to the mechanoreceptors on the feet thereby impairing the ability to maintain postural control and increasing vibration detection threshold (Stal et al., 2003).

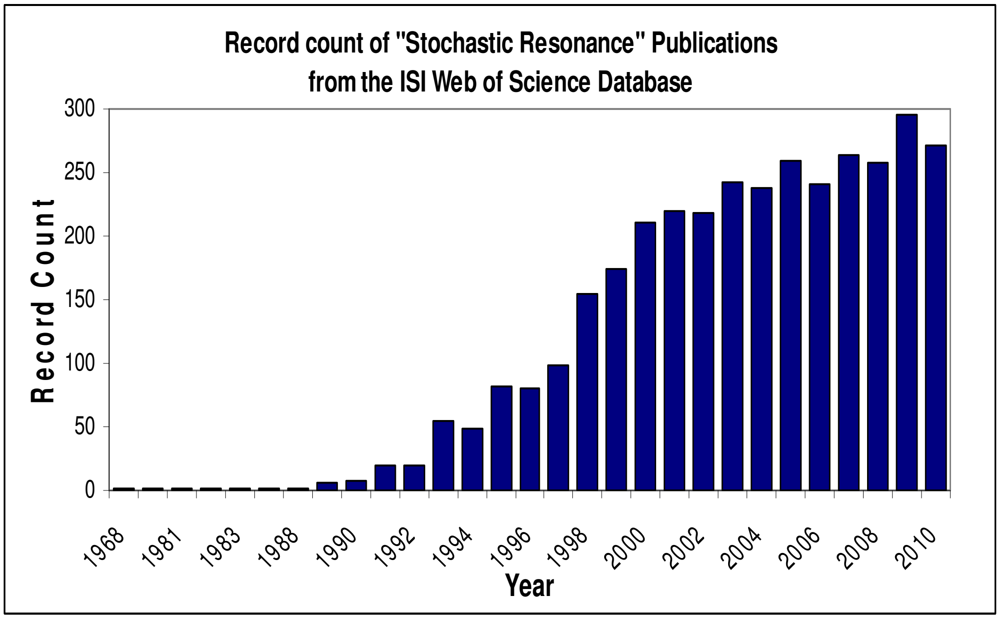
Patients with loss of sensitivity in the soles of the feet (i.e. diabetic neuropathy) (J. M. Hijmans et al., 2008; Khaodhiar et al., 2003; Priplata et al., 2006) and those who failed to integrate peripheral somatosensory information (i.e. stroke) (Priplata et al., 2006) showed postural instability. Tactile vibration stimulation on the plantar foot surface have been used to study and improve postural and balance control in these patients. Therefore, sensory information from the cutaneous mechanoreceptors on the plantar surface of the foot contributes significantly in postural control and stability.

2.2 Stochastic Resonance Postural Research

Stochastic resonance is the phenomenon wherein the response of a nonlinear system to a weak periodic and aperiodic input signal is optimized by the presence of a nonzero level of noise (Benzi, Sutera, & Vulpiani, 1981; Collins, Imhoff, & Grigg, 1996). McDonnell and Abbott (2009) described it as the phenomenon where random noise causes an increase in detection performance or quality of signal transmission of a nonlinear system rather than a decrease. Noise is normally known to interfere with signal detection and system performance. But several studies have shown that the addition of noise to a sub-threshold signal makes a signal detectable (Priplata et al., 2006; Wells et al., 2005) .

Stochastic resonance has been the topic of research since 1968 and the term "stochastic resonance" has been used in about 3,505 publications according to the ISI Web of Science database (Figure 2-1). An increase in the popularity can be observed that started in year 1991 where a weak periodic signal can be assisted by detection and amplification by noise (Bulsara, Jacobs, Zhou, Moss, & Kiss, 1991; Dykman, Velikovich, Golubev, Luchinskii, & Tsuprikov, 1991; Fulinski & Telejko, 1991; Jung & Hanggi, 1991; Moss, 1991) and have remained in about 6% to 7% (out of 3,505) from year 2000 to 2006. It again gained popularity in 2007 to 2010. For the first quarter of the year 2011, about 35 publications showed up in the query. Stochastic resonance has been studied in multidisciplinary field: about 77% were focus in the field of physics followed by disciplines in neuroscience, engineering, and mathematics that were all approximately 6%, the 4% in biology and only 0.23% accounts for rehabilitation.

Figure 2-1. Record count of publications on “Stochastic Resonance” from ISI Web of Science database by year



2.3 Vibration and Posture

The search criteria were filtered to research studies involving posture and balance in human with the application of noise on the sole of the feet. There were nine papers included in the assessment of this review. Most of the studies used vibratory noise in the frequency range 0 to 100 Hz and one used 25Hz to 500Hz (J. M. Hijmans et al., 2008) and subjects ranged from healthy adults to elderly non-fallers and fallers to patients with diabetes, stroke, and chronic bilateral vestibular loss. Application of vibration noise on the sole of the foot was observed to improve vibration and tactile perception in diabetic patients (Khaodhiar et al., 2003), reduced postural sway in healthy young subjects and elderly (Priplata, Niemi, Harry, Lipsitz, & Collins, 2003; Priplata et al., 2006) during quiet stance and stride, stance and swing time during gait (Galica et al., 2009) due to the

SR phenomena. Subjects with chronic vestibular loss (Maurer et al., 2001) and subjects with diabetic neuropathy, stroke, and elderly fallers (J. M. Hijmans et al., 2007; Priplata et al., 2006) were also shown to improve posture with noise. The vibration noise was also shown to increase postural control system's complexity (Costa et al., 2007) with noise. Though some of these studies did not show any difference in postural sway with vibration noise in healthy adults (J. M. Hijmans et al., 2008; Kristinsdottir, Fransson, & Magnusson, 2001). This difference in results maybe caused by the difference in outcome measure used where one uses torque variance and the other uses mean and RMS of COP displacement velocities.

Table 2-1. : Summary of the research studies in stochastic resonance phenomena with the application of noise to human plantar foot surface and the responses on postural measures

Author(s)	Title	Vibration Noise	Outcome Measures	Conclusion
Maurer (2001)	Human balance control during cutaneous stimulation of the plantar soles	~0.2 Hz 0.05, 0.1, 0.2, and 0.4 Hz	FFT on COP, COP displacement , angular displacement, COM	The COP shifts were associated with an equally small counter-phase angular displacement of the hip, while the shoulders (upper body) remained stationary in space or were moved slightly in-phase with the stimulus
Kristinsdottir (2001)	Changes in Postural Control in Healthy Elderly Subjects are Related to Vibration Sensation, Vision and Vestibular Asymmetry	vibratory effect was 850 mW (1.0 mm amplitude at 60 Hz)	torque variance	No difference in sway variance between the adults and the elderly subjects with normal sensation.
Roll (2002)	Cutaneous afferents from human plantar sole contribute to body posture awareness	30 vibrators under the main supporting areas of each foot 0 to 100 Hz with a set amplitude of 0.5 mm.	COP	Illusory perceptions of whole-body leaning were reported. Both orientation and amplitude of these perceptions depended on the stimulation pattern.
Khaodhiar et. al. (2003)	Enhancing sensation in diabetic neuropathic foot with mechanical noise	C2 mechanical actuators (frequency range not specified)	Semmes-Weinstein Filament (SWF) detection rate	Improved vibration and tactile perception in diabetic patients with severe neuropathy
Priplata et. al. (2003)	Vibrating insoles and balance control in elderly people	sub-threshold white noise signal low pass filtered to 100Hz	stabilorgram mean radius and swept area, AP and ML range of a single marker on the shoulder normalized by height of the shoulder, critical mean square isplacement, diffusion coefficent and long term scaling exponent	Reduction in sway parameters in young participants and in elderly participants

Priplata et. al. (2006)	Noise-Enhanced Balance Control in Patients with Diabetes and Patients with Stroke	sub-threshold white noise signal, low-pass filtered to 100Hz and distributed uniformly in amplitude	mean stabilogram radius, area swept by the stabilogram over time , the maximum radius of sway , and the range of the AP and ML excursions	All of the sway parameters among the subjects with diabetic neuropathy, subjects with stroke, and healthy elderly subjects decreased with the application of noise
Costa et. al. (2007)	Noise and poise: Enhancement of Postural complexity in the elderly with a stochastic-resonance based therapy	sub-threshold white noise signal low pass filtered to 100Hz	Multiscale entropy (MSE) of COP displacement and velocity time series	Postural sway dynamics of healthy individuals are the most complex and that the control system's complexity degrades with disease.
Hijmans et. al. (2008)	Effects of vibrating insoles on standing balance in diabetic neuropathy	vibrating insoles consisted of a cork sole with three built-in piezoelectric elements 25 to 500 Hz	mean velocity of the COP displacements and RMS of the velocity of these displacements in the AP and ML directions	In subjects with neuropathy, an interaction effect between vibration and an ADT was found for balance. No effects of vibration on balance were found in nondisabled subjects. Vibrating insoles improved standing balance in subjects with neuropathy only when attention was distracted.
Galica et. al. (2009)	Subsensory vibrations to the feet reduce gait variability in elderly fallers	C2 mechanical actuators with Gaussian white noise, band-limited to 100 Hz	differences in stride, stance, and swing time variability	Reduced stride, stance, and swing time variability measures for elderly recurrent fallers. Elderly non-fallers also demonstrated significant reductions in stride and stance time variability. Although young participants showed decreases in all variability measures, the results did not achieve statistical significance.

2.4 Vibration and Vision in Posture and Balance

Vision provides an important sensory information in postural control and balance. Increased responsiveness in visual sensory information suggests the shift of reliance in the vision system (Keshner, Kenyon, & Langston, 2004; Streepey, Kenyon, & Keshner, 2007). Somatosensory and visual system sensory information are integrated to interpret a complex sensory environment. The need to re-weight the relative dependence on each of the senses is essential for maintaining stability as the sensory environment changes (Horak, 2006). Sensory pathways that are simultaneously feeding inputs into the system exhibits a non-linear behavior and is unlikely that the role of a single pathway can be characterized in a static environment (Keshner et al., 2004). Vision plays an important role in postural control and balance especially in a challenging conditions when sensory information from the feet and ankles are reduced or changed. Therefore, having a stable visual surround is necessary for the postural control system to utilize visual information when other sensory inputs are altered (Adamcova, 2007; Lord, 2000).

2.5 Vibration and Attention Level in Posture and Balance

Attention also plays an important role in postural control. Attention can be defined as the individual's capacity of information processing (Woollacott & Shumway-Cook, 2002). Simultaneous inputs from the multiple pathways (visual, somatosensory, and vestibular) may affect postural control in relation to information processsing and capacity where cognitive task may interfere or enhance postural control. Cognitive functioning and control of posture and balance are related to some extent (Andersson, Hagman, Talianzadeh, Svedberg, & Larsen, 2003). Postural control has been observed to involve either automation, cognition, or both. Stins et. al (2010) demonstrated that postural control was influenced by affective and cognitive interventions in terms of attentional investment in posture and neuromuscular regulation.

CHAPTER 3

METHODOLOGY

3.1 Development of the Vibrating Footwear

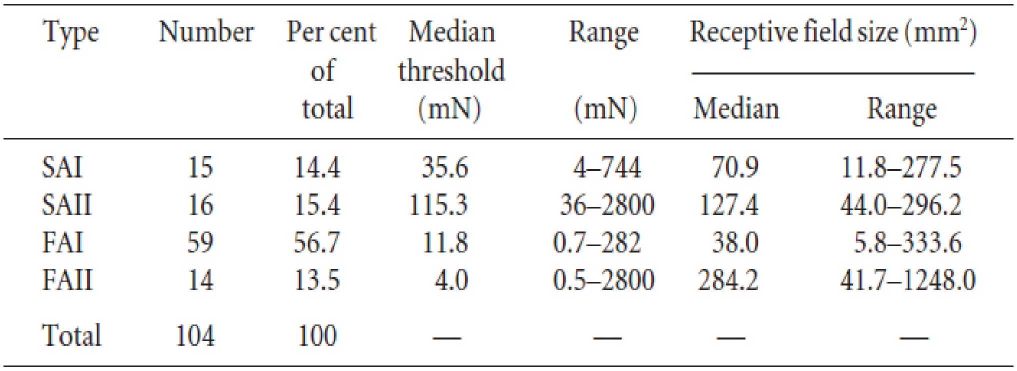
The main reason for the development of the vibrating footwear is to study the effect and mechanism of vibratory noise in postural control and balance. The vibrating footwear was designed so it is easy to wear and subjects will be comfortable wearing it throughout the duration of the experiment. The use of flip flops was implemented to support ease and comfort as well as familiarity with the mode of footwear.

The main focus is on the stimulation of the cutaneous mechanoreceptors on the plantar foot surface. Tactile stimuli, detected by the cutaneous mechanoreceptors (Meissner's corpuscles, Pacinian corpuscles, Merkel's disks and Ruffini endings) provide the CNS with information about spatial distribution of stimulation that is translated into a body position indicating the direction and amplitude of the body inclination (Hijmans et al., 2007; Kavounoudias et al., 1998). The mechanoreceptors located all over the body are able to sense the vertical and horizontal components of ground reaction forces. There are four types of mechanoreceptors classified according to the rate of adaptivity (slow or fast adapting) and receptive field (type I or type II) which are associated with the four different types of afferent nerves (Kennedy & Inglis, 2002; Ribot-Ciscar et al., 1989; Wells et al., 2003). Slowly adapting (SAI and SAII) produces sustained response to maintained stimulus while fast adapting (FAI and FAII) produces respose to change in state of stimulus. Type I receptors (SAI and FAI) has small receptive fields while type II

(SAII and FAII) have large receptive fields. SAII receptors are sensitive to frequencies below 8 Hz while type I receptors (SAI and FAI) are sensitive to frequencies 2-32 Hz and 8-64 Hz respectively. Frequencies above 64 Hz are mediated by FAII receptors (Wells et al., 2005). FAI and FAII have high sensitivity to vibrations while SAI and SAII are sensitive to touch and pressure. Table 3.1- shows the different types of mechanoreceptors and its profiles and Figure 3.1-1 shows that distribution of these mechanoreceptors (Kennedy & Inglis, 2002). The accumulation of the receptors on the metatarsal phalangeal joint (MTP) region and the heel region of the foot corresponds to the critical regions of the foot also where the majority of the body's weight is under loaded conditions (Kennedy & Inglis, 2002; Perry, McIlroy, & Maki, 2000). Therefore the vibrotactile actuators were positioned on the footwear accordingly; two on the MTP and one on the heel (Figure 3.1-2).

Merkel's discs (SAI) and Ruffini's ending (SAII) mechanoreceptors were shown to contribute to postural control during standing balance (Hamalainen et. al., 1992; Perry et al., 2000). The actuator chosen was a small coin-shaped DC motor (Figure 3.1-3) with a shaft that rotates about 12000±3000 rpm creating a centrifugal force that is transmitted through the entire motor as vibration at frequency of approximately 10 Hz to 55 Hz. The motor dimensions are 8.0 ± 0.5 mm in diameter and 3.4mm thick. Each element received a random pulse signal, generated by a computer program (MATLAB), and sent to the data acquisition board (NI DAQ PCI 6259) to turn the vibrating elements on and off (5-500Hz) , thus generating vibratory noise stimulation on the plantar foot surface. A potentiometer (10K –Ohm wheel, 0.5W) of each actuator was used to adjust the amplitude of the signal until the vibration stimulus was at the subject's threshold level (i.e., vibration is just noticeable). Then the potentiometers were increased to lower the amplitude of the vibration signal to approximately 90% below threshold level.

Table 3.1-1. Profiles of cutaneous mechanoreceptors in the foot sole, after (Kennedy & Inglis, 2002)



Type	Number	Per cent of total	Median threshold (mN)	Range (mN)	Receptive field size (mm²)	
					Median	Range
SAI	15	14.4	35.6	4–744	70.9	11.8–277.5
SAII	16	15.4	115.3	36–2800	127.4	44.0–296.2
FAI	59	56.7	11.8	0.7–282	38.0	5.8–333.6
FAII	14	13.5	4.0	0.5–2800	284.2	41.7–1248.0
Total	104	100	—	—	—	—

Figure 3.1-1. Distribution of cutaneous mechanoreceptors in the foot sole. The receptive field in each receptor type in the foot sole is illustrated, after (Kennedy & Inglis, 2002)

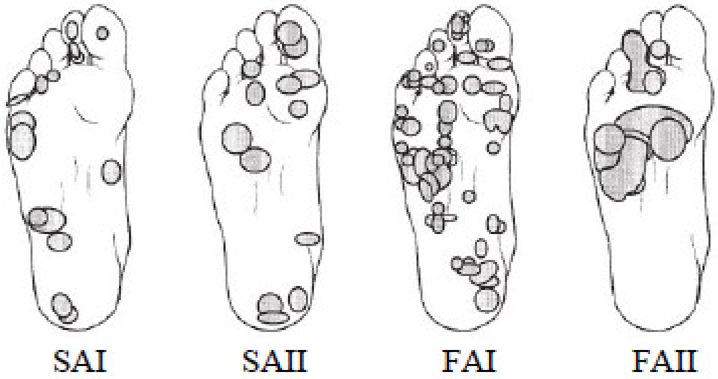
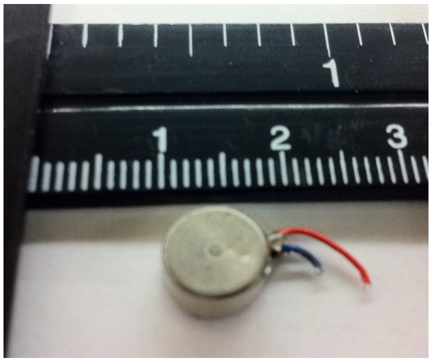


Figure 3.1-2. Open-type footwear (flip-flops) with the embedded vibrator motors on the heel and two on the metatarsal phalangeal joint.

Figure 3.1-3. DC Vibrator Motor Part # C0834B011F



3.2 Vision System

Most studies examining the effect of vision on postural responses to vibration on the plantar foot surface have only investigated the effects with earth-fixed visual inputs or eyes-closed. Somatosensory and visual system sensory information must be integrated to interpret a complex sensory environment. Sensory pathways that are simultaneously feeding inputs into the system exhibits a non-linear behavior and is unlikely that the role of a single pathway can be characterized in a static environment (Keshner et al., 2004). The frequency and velocity of the visual scene were chosen for the following criteria that it was large enough to elicit a physical response. Previous studies conducted at the lab using a constant velocity of 30°/second have shown to immerse the subject in subject in visual flow.

Subjects stood within a three-wall virtual environment (CAVE) that closely resembles natural visual conditions (Figure 3.2-1.). The CAVE is a rectagular space measuring 269 cm x 269 cm x 206 cm (width x depth x height). The CAVE consists of three screens of back projection material placed in front and to the left and right sides of the subject. The visual scenes were created on a Windows based PC and are back-projected on the screens with six DLP projectors (Panasonic PT-5600). The visual scene consists of small spheres randomly distributed across the three screens. Subjects wore stereo glasses over any corrective lenses to elicit a 3 dimensional (3D) efffect. The visual scene conditions were eyes closed, eyes open with stationary scene, or rotating in a pitch-up direction at 30°/sec.

Figure 3.2-1. The three-wall virtual environment (CAVE) with virtual images of random size spheres on a black background projected on the three screens (front, left and right). Subject is standing on the dual force plates.

3.3 Dual Task Paradigm

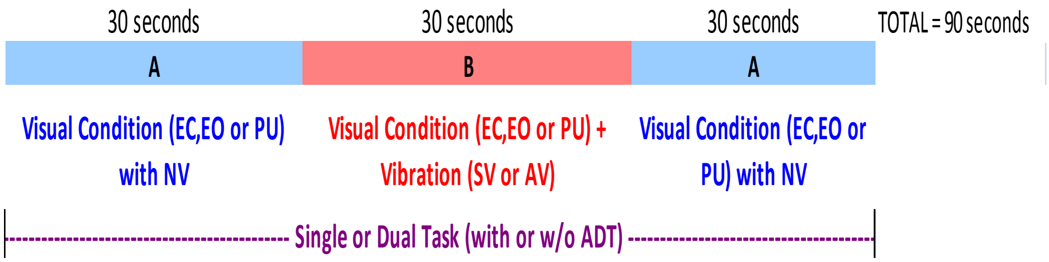
The dual task paradigm in this study was designed to assess the effects of the allocation of attention to either the cognitive task or postural control task when different levels of vibration were applied. Simultaneous inputs from the multiple pathways (visual, somatosensory, and vestibular) may affect postural control in relation to information processsing and capacity where cognitive task may interfere or enhance postural control.

A computational cognitive task was used in this paradigm to be able to generate changes in postural perfomance (Chong et al., 2010). The dual task paradigm consist of a computation task by reciting the Fibonacci sequence starting at two consecutive random numbers picked out before the test begins. The Fibonacci sequence is a series of numbers where the next number is found as the sum of the previous two number in the sequence.

3.4 Protocol

The subjects were asked to stand on the force platform inside the CAVE subjected to the visual stimulus and the dual task paradigm or a single task of standing quietly. The vibration stimulus was either sub-threshold or above threshold level. The subjects were standing on a compliant surface (dense foam 6.5 cm thick) for the 12 trials (3 visual conditions x 2 vibration levels x 2 attention demanding task). Each trial lasted for 90 seconds. The first 30 seconds had no vibration followed by 30 seconds of either sub-threshold or above-threshold vibration then the last 30 seconds of no vibration (Figure 3.4-1). The combination of all the conditions are listed on Appendix C and were presented in random order for each subject. The subject were given a rest period where they sat on a chair in between trials or do leg stretches to avoid muscle fatigue.

Figure 3.4-1. Protocol with visual conditions of eyes closed (EC), eyes open and pitch-up scene (PU). The vibration will either be on a sub-threshold (SV) level or above-threshold (AV) level. The subject performed a single task of standing quietly or a dual task. The first 30 seconds and the last 30 seconds of the trial had no vibration (NV). The vibration (SV or AV) were turned on during the middle 30 seconds of the trial.



3.5 Subjects

Twenty one healthy adults (7 women and 14 men; age range 20-29 years old) participated in this study. All subjects had a minimum of 20/40 corrected vision in each eye and adequate hearing to listen to instructions from the investigator standing behind them throughout the experiment. All subjects had no history of central or peripheral neurological disorders or problems related to movements of the spinal column (e.g., significant arthritis or musculoskeletal abnormalities), and gave informed consent as approved by the Temple University Institutional Review Board (IRB).

3.6 Procedures

Prior to any testing, subjects were provided with the Subject Information and Consent form. They were given ample time to read it and the opportunity to receive answers to any questions they have. The testing proceeded only after subjects were comfortable that they understood the form and had signed it.

At the beginning of the test session, a filament evaluation test (See Appendix A) was conducted to determine the level of sensation of the subject’s feet using a 10-g

Semmes-Weinstein Monofilament (SWM) on the great toe and lateral side of the foot for both left and right feet. Subjects were tested with the 10-g SWM using three filament sizes 4.17, 5.07 and 6.10. The SWM exerts 10 grams of force when bowed into a C-shape against the skin for one second. Subjects were excluded if sensation on the plantar surface of the feet was absent when tested with the largest filament. All twenty one subjects in this study passed the filament test and no one was excluded.

To test for vibrotactile sensitivity, a 128Hz tuning fork was applied perpendicularly with constant pressure on the heel of each foot. Without looking, subjects reported whether the tuning fork was vibrating or not. The vibrotactile sensitivity test was used to determine if the subject was able to differentiate the sensation of vibration from that of pressure from the contact of the tuning fork. The subjects were asked to keep their eyes closed during the filament evaluation test and vibrotactile sensitivity test.

Each subject was instructed to put on the vibratory footwear to obtain their vibration threshold level. Each vibrator motors were turned on and the potentiometers were adjusted independently for all six vibrator motors until the subject reported that a just noticeable vibration was felt. The stimulation level was then set to approximately 90% of the threshold level for sub-threshold vibration stimuli.

Subjects were instructed to put on the vibratory footwear and to stand comfortably and maintain an erect posture while standing on a compliant surface. At the beginning of each trial, the investigator gave the subject instructions to either keep their eyes closed or open and whether to do single task or dual task.

3.7 Data Collection and Analysis

A NeuroCom (NeuroCom International Inc., Clackamas, Oregon) force plate platform was used to collect the forces and COP data during the test. The ground reaction forces were collected to calculate COP.

Kinematic data (time and marker positions) were collected from 34 infrared markers placed on the subject's head and body and captured by a motion analysis system Cortex (Motion Analysis Corp., Santa Rosa, California). Subjects' identities cannot be obtained from this system which is only sensitive to infrared signals. All results were identified by subject number and not identified by name.

The COP and COM 90 seconds data for each trial were divided in three 30 seconds time period: pre-vibration (time 1), on vibration (time 2), and post vibration (time3). The root mean square (RMS) and ellipse area for the each time periods (time 1, time2 , and time 3) for the COM and COP in the anterior-posterior (AP) and medio-lateral (ML) directions over were calculated. All data collected were processed using MATLAB.

3.7.1 Center of Mass

Kinematic data from the infrared markers and motion analysis system were collected and the whole body center of mass excursions were computed with reference to anthropometric data (Winter, 1990). The marker data were collected at 120Hz and low-pass filtered using fourth order Butterworth filter with a cut-off frequency of 4Hz. The data were then normalized by subtracting their initial position.

3.7.2 Center of Pressure

COP is the point of vertical ground reaction force vector that represents a weighted average of all the pressures over the surface of contact with the platform. The COP data were collected using the NeuroCom Research Module. The NeuroCom Research Module has two independent force plates (left and right) and each force plate measures three forces (Fx, Fy, Fz) and three moments (Mx,My,Mz) and calculates the total COP (Appendix B). The force plate data were sampled at 200Hz and then normalized to the subject's initial position by subtracting the initial position data from each trial for every time period (pre-vibration, on vibration and post vibration).

3.7.3 Ellipse Area

The COP and COM excursions in the AP and ML directions were analyzed by computing the area of excursion using principal component analysis (PCA). In this method, the area of excursion was estimated by fitting an ellipse to the COP and COM covariance matrix data to include 85% of the data points. The two main axes of the ellipse were found by calculating the eigenvalues of the covariance matrix between the AP and ML data (Duarte & Zatsiorsky, 2002; Latash, Ferreira, Wieczorek, & Duarte, 2003). The first eigenvector of the covariance matrix is the direction of the principal axis and the corresponding largest eigenvalue is the variance along this axis. The second eigenvector which is orthogonal to the first eigenvector defines the direction of the minor axis and the corresponding eigenvalue is the variance along this axis (Oliveira, Simpson, & Nadal, 1996).

3.7.4 Approximate Entropy

Researches on statistics suggests that ApEn can classify complex systems given at least 1000 data values in diverse settings that include both deterministic chaotic and stochastic processes (Pincus, 1991). ApEn was calculated to determine the unpredictability of the time series of the COP and COM excursions. To calculate ApEn for a time series containing N data points, $u(1), u(2), u(3), \ldots u(N)$, two parameters were chosen, r and m. The r parameter defines the error tolerance and the m parameter defines the pattern length.

First step was to define a sequence of vectors $x(1), x(2), \ldots x(N-m+1)$ where

$$x(i) = [u(i), u(i+1), \ldots, u(i+m-1)].$$

Second step was to define the $d[x(i), x(j)]$ for vectors $x(i)$ and $x(j)$.

$$d[x(i), x(j)] = \max (|u(i+k-1) - u(j+k-1)|) \ , k = 1,2,\ldots m$$

The third step was to find the $C^{m}_{i}(r)$ values which measures (within the tolerance r) the regularity of patterns similar to a given pattern of window length m for each i, $1 \leq i \leq N - m - 1$.

$$C^{m}_{i}(r) = (\text{number of j such that } d[x(i), x(j)] \leq r)/(N - m + 1)$$

The fourth step was to define $\Phi m(r)$ as the average value of the natural logarithm of $C^{m}_{i}(r)$. Lastly, ApEn is calculated as

$$\text{ApEn}(m,r,N) = \Phi m(r) - \Phi m{+}1\ (r)$$

ApEn results in a unit-less value from 0 to 2 where smaller values of ApEn imply greater probability of repeating sequences of m observations.

The ApEn values were calculated for the AP components of COP and COM over the three time periods (pre-vibration, on vibration and post-vibration) for a test duration of $N_{COP}=6000$ (30 seconds x 200 Hz) and $N_{COM}=3600$ (30 seconds x 120 Hz) for each trial. The parameters used for r, m and lag were 0.2, 2 and 10, respectively, based on previous reports in the literature (Cavanaugh et al., 2005; Cavanaugh et al., 2007; Dusing et al., 2009; Pincus, 1991).

3.7.5 Statistics

The effects of the vibration study on healthy adults' postural responses were tested for statistical significance using repeated measures analysis of variance (ANOVA) with the within-subject factors of vision (3 levels: eyes closed, eyes open and pitch-up scene), task (2 levels: single task and dual task), and vibration level (2 levels: sub-threshold vibration and above-threshold vibration) at a 95% confidence level ($p<0.05$). Contrast tests were conducted for priori analyses. Bonferroni confidence adjustment was also used to compare the means ($p=0.05/28$) . IBM SPSS Statistics (version 19, IBM Corporation, Somers, New York) program was used for all statistical analyses.

CHAPTER 4

RESULTS

4.1 The Effects of Dual Task

Dual task had significant main effects for COP ML time series [F(1,20)=4.62, *p*=0.04] and COM AP time series [F(1,20)=6.22, *p*=0.02] becoming more random (higher ApEn value) as compared to single task. Only COP ML ApEn and COM AP ApEn (Table 4.1-1) showed significant difference between single task and dual task conditions.

Table 4.1-1: Task (single task and dual task) main effects. Highlighted *p*-value shows significant results.

SOURCE:		TASK		
MEASURES	**numerator df**	**denominator df**	**F**	**p-value**
COP-AP RMS	1	20	0.374	0.548
COP-ML RMS	1	20	0.205	0.656
COP-AP APEN10	1	20	4.203	0.054
COP-ML APEN10	1	20	4.62	0.044
COP AREA	1	20	0.944	0.343
COM-AP RMS	1	20	0.026	0.872
COM-ML RMS	1	20	0.008	0.930
COM-AP APEN10	1	20	6.225	0.021
COM-ML APEN10	1	20	2.883	0.105
COM AREA	1	20	2.38	0.139

4.2 The Effects of Vision

Vision (eyes closed, eyes open, and pitch-up) resulted in significant main effects on COP and COM as shown on Table 4.2-1. Vision had significant effects where pitch-up visual scene significantly increased COP AP and ML RMS, COM AP RMS, COP and COM areas, and COP AP ApEn (*p*<0.05/3=0.016). Eyes open condition did not differ with eyes closed condition for RMS and area. COP AP and ML and COM AP ApEn significantly decreased with eyes open condition as compared to eyes closed condition.

Table 4.2-1: Vision (eyes-closed, eyes-open and pitch-up) main effects. Highlighted *p*-value shows significant results at *p*<0.05.

SOURCE:		**VISION**		
MEASURES	**numerator df**	**denominator df**	**F**	**p-value**
COP-AP RMS	1.3	26.9	30.78	0.000
COP-ML RMS	1.6	31.4	17.046	0.000
COP-AP APEN10	1.6	31.3	37.208	0.000
COP-ML APEN10	1.9	38.7	4.266	0.022
COP AREA	1.1	2.2	12.127	0.002
COM-AP RMS	1.7	34.9	16.109	0.000
COM-ML RMS	1.6	31.2	4.918	0.020
COM-AP APEN10	2	40	17.329	0.000
COM-ML APEN10	2	40	1.246	0.299
COM AREA	1.2	23.1	15.806	0.000

4.3 The Effects of Vibration Noise and Vibration Level

Time (time 1, time 2 and time 3) resulted in significant main effects on COP and COM as shown on Table 4.3-1. Main effects of time resulted in a priori contrasts of significant difference for time 2 (on vibration) versus time 1 (pre-vibration) and for time 3 (post vibration) versus time 1 (pre-vibration) for COP and COM RMS and ApEn except for COP ML RMS time 2 versus time 1. COP and COM RMS increased with time while ApEn values decreased with time regardless of the vision, task and vibration level. On the other hand, RMS, ApEn, and area for COP and COM measures did not reveal a significant main effects for the vibration levels (sub-threshold and above-threshold) as shown on Table 4.3-2.

Table 4.3-1: Time (pre-vibration, vibration, and post-vibration) main effects. Highlighted *p*-value shows significant results.

SOURCE:		TIME		
MEASURES	**df**	**error df**	**F**	**p-value**
COP-AP RMS	1.3	26.3	9.438	0.003
COP-ML RMS	1.4	28.4	12.531	0.000
COP-AP APEN10	2	40	16.769	0.000
COP-ML APEN10	1.9	38.1	64.289	0.000
COP AREA	1.5	29.2	2.174	0.143
COM-AP RMS	1.8	36.7	16.746	0.000
COM-ML RMS	1.3	26.6	20.753	0.000
COM-AP APEN10	2	40	8.850	0.001
COM-ML APEN10	2	40	47.169	0.000
COM AREA	1.5	30.9	4.127	0.035

Table 4.3-2: Vibration level (sub-threshold vibration and above-threshold vibratio) main effects. No significant results within-in subject interactions for vibration levels.

SOURCE:		VIBRATION		
MEASURES	**numerator df**	**denominator df**	**F**	**p-value**
COP-AP RMS	1	20	0.647	0.431
COP-ML RMS	1	20	0.221	0.644
COP-AP APEN10	1	20	1.159	0.294
COP-ML APEN10	1	20	0.323	0.576
COP AREA	1	20	0.123	0.73
COM-AP RMS	1	20	0.125	0.728
COM-ML RMS	1	20	0.275	0.606
COM-AP APEN10	1	20	0.161	0.692
COM-ML APEN10	1	20	0.15	0.703
COM AREA	1	20	0.327	0.574

4.4 The Effects of the Interaction between Vibration Noise and Dual Task

The COM AP ApEn was the only measure that showed significant difference in interaction of the vibration noise and task conditions (Table 4.4-1). Priori contrast showed a significant difference between T1 (pre-vibration) and T2 (on vibration) with task condition (single task vs. dual task) (Table 4.4-2). COM AP ApEn become less random (lower ApEn) when vibratory noise was applied while performing a dual task (Figure 4.4-1). No significant difference was seen with the applied vibration noise while performing a single task.

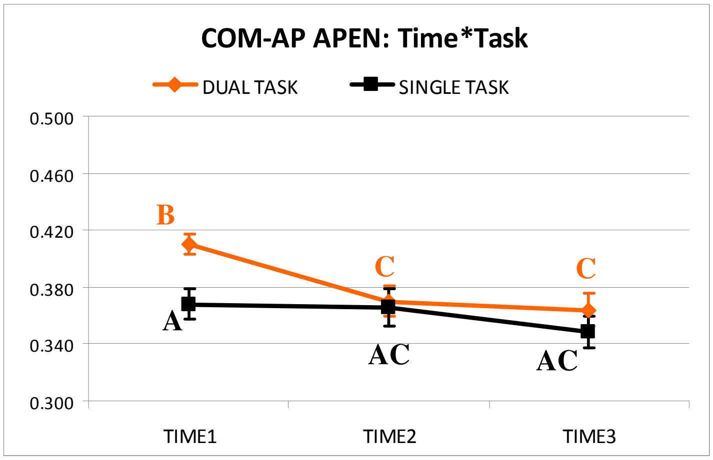
Table 4.4-1: Time*Task *p*-value for COP and COM postural responses in AP and ML directions. Highlighted *p*-value shows significant results.

MEASURES	df	Error df	F	p-value
COP-AP RMS	2	40	0.571	0.569
COP-ML RMS	1.4	27	0.25	0.693
COP-AP APEN	2	40	1.312	0.281
COP-ML APEN	1.9	37.6	0.107	0.888
COP AREA	1.7	34.1	0.09	0.886
COM-AP RMS	2	40	2.585	0.088
COM-ML RMS	1.4	28.4	0.003	0.988
COM-AP APEN	1.9	37.9	6.039	0.006
COM-ML APEN	2	40	0.073	0.929
COM AREA	1.6	31.7	0.031	0.944

Table 4.4-2: Priori contrast results for Time*Task for COM ApEn in AP direction. Highlighted *p*-value shows significant results. (Legend: T1 – pre-vibration 1, T2 – on vibration, T3 – post vibration, ST – single task, DT – dual task)

SOURCE:		TIME*TASK			
MEASURES	Source	df	error df	F(1,20)	p-value
COM-AP APEN	T2 vs T1, DT vs ST	1	20	12.781	0.002
	T3 vs T1, DT vs ST	1	20	7.827	0.011

Figure 4.4-1: Time*Task means of the COM ApEn in AP direction across time (pre-vibration, on vibration, and post-vibration) for single and dual task. The means on the graph with the same letter indicate no statistical significance between times (Boferroni adjustment, *p=0.05/6 =0.008*) per task. Standard error represented by the vertical bars.



4.5 The Effects of the Interaction between Vibration Noise and Vision

Time and vision showed a significant interaction for COP and COM ApEn in AP direction (Table 4.5-1). Priori contrast showed a significant difference for pre-vibration and during vibration with eyes closed and pitch-up visual condition (Table 4.5-2). The COP and COM time series in AP direction become less random (lower ApEn value) with time (pre-vibration, on vibration, and post vibration) for eyes closed and eyes open visual conditions (Figure 4.5-1). COP and COM ApEn did not change with time when vibratory noise was applied and after it was removed when subjected to a pitch-up visual condition.

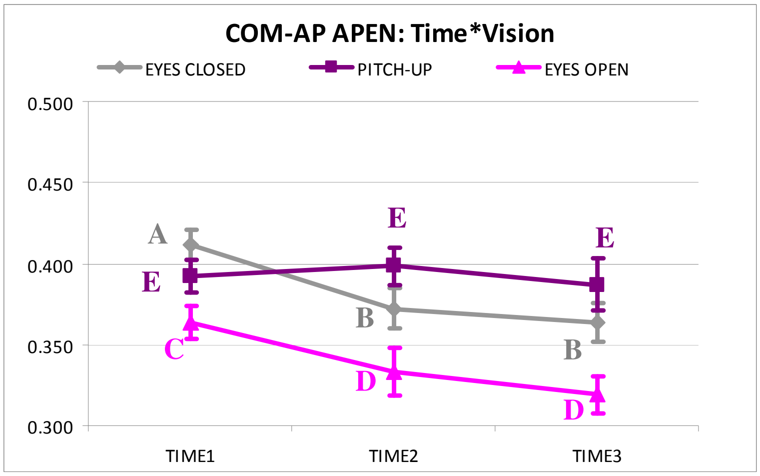
Table 4.5-1: Time*Vision *p*-value for COP and COM postural responses in AP and ML directions. Highlighted *p*-value shows significant results.

MEASURES	df	Error df	F	p-value
COP-AP RMS	3.7	74.4	1.765	0.149
COP-ML RMS	4	80	1.052	0.386
COP-AP APEN	4	80	3.554	0.01
COP-ML APEN	4	80	1.533	0.201
COP AREA	2.3	45.4	0.953	0.403
COM-AP RMS	4	80	1.503	0.209
COM-ML RMS	2.3	45.6	0.365	0.724
COM-AP APEN	3.9	79.1	3.188	0.018
COM-ML APEN	4	80	1.318	0.270
COM AREA	2.7	53.9	2.65	0.064

Table 4.5-2: Priori contrast results for Time*Vision for COP and COM ApEn in AP direction. Highlighted *p*-value shows significant results. (Legend: T1 –pre-vibration, T2 – on vibration, T3 – post vibration, EO – eyes open, EC – eyes closed, PU – pitch up)

SOURCE:		TIME*VISION			
MEASURES	**Source**	**df**	**error df**	**F**	**p-value**
COP-AP APEN	T2 vs T1, EO vs EC	1	20	0.004	0.947
	T2 vs T1, PU vs EC	1	20	6.53	0.019
	T3 vs T1, EO vs EC	1	20	0.516	0.481
	T3 vs T1, PU vs EC	1	20	6.819	0.017
COM-AP APEN	T2 vs T1, EO vs EC	1	20	0.317	0.58
	T2 vs T1, PU vs EC	1	20	12.286	0.002
	T3 vs T1, EO vs EC	1	20	0.039	0.845
	T3 vs T1, PU vs EC	1	20	6.979	0.016

Figure 4.5-1: Time* Vision means of the COM AP mean ApEn across time (pre-vibration, on vibration, and post-vibration) for eyes closed (EC), eyes open (EO) and pitch-up (PU). The means on the graph with the same letter indicate no statistical significance between times (Boferroni adjustment p=0.05/9 =0.006) per vision for each graph. Standard error represented by the vertical bars.



4.6 The Effects of the Interaction between Vibration Noise, Vision and Vibration Level

A three-way interaction for time, vision and vibration level for COP AP ApEn resulted to a significant *p*-value (Table 4.6-1). Significant interaction of time before and during application of vibratory noise (pre-vibration vs. on vibration) for sub-threshold (SV) and above-threshold (AV) vibration level when vision was pitch-up scene compared to when eyes were closed (Figure 4.6-1). The vibration level (SV vs. AV) had a different effect on the postural responses interaction between vibration noise and vision. Eyes closed and eyes open slightly decrease COP AP ApEn when AV was applied but not significantly. A significant decrease in randomness (lower ApEn) resulted after the vibratory noise was removed for both eyes closed and eyes open conditions. On the other hand, when SV was applied, time and vision interaction was significant [$F(4,80) = 6.7$, $p<0.05$] where COP AP ApEn significantly decreased randomness (lower ApEn) during application of SV and also after SV was removed (post vibration) for both eyes closed and eyes open conditions. During pitch-up visual condition, COP AP ApEn slightly increased when SV was applied but not significantly. Vibration levels, SV and AV did not significantly affect COP AP ApEn for pitch-up vision. A three way interaction was also found for time (pre-vibration, on vibration and post vibration), vision (eyes closed, eyes open and pitch-up) and vibration level (SV vs. AV) significant difference for COP RMS in AP and ML direction and COP area (Table 4.6-2). Priori contrast analysis showed significant interaction for COP AP RMS between vibration level, SV versus AV, when vibratory noise was applied (Time 1 vs. Time 2) when subjected to a pitch-up visual condition (Figure 4.6-2). Vibration level, SV and AV showed the same effect when vibratory noise was applied during eyes closed condition. No significant change was also seen for eyes open visual condition for the interaction between vibration and vibration level. Therefore, eyes closed and eyes open visual conditions did not have any significant within subject interaction between time and vibration level.

Priori contrast for COP RMS in ML direction showed significant results of interaction between vibration noise before (pre-vibration) and after (on vibration) application of vibratory noise between eyes open versus eyes closed when sub-threshold vibration level was applied (Figure 4.6-3). The applied SV significantly increased COP ML RMS during eyes open visual condition and after it was removed. In contrast, AV did not have any significant interaction with the eyes open and eyes closed visual conditions for COP ML RMS.

Table 4.6-1: Time*Vision*Vibration *p*-value for COP and COM ApEn in AP and ML direction. Highlighted *p*-value shows significant results.

MEASURES	df	Error df	F	p-value
COP-AP APEN	3.9	77.5	3.134	0.02
COP-ML APEN	4	80	1.513	0.206
COM-AP APEN	4	80	0.706	0.590
COM-ML APEN	4	80	1.622	0.177

Figure 4.6-1: Time*Vision*Vibration means of the COP AP ApEn sub-threshold vibration. Priori contrast for Time1 (pre-vibration) vs. Time2 (on vibration), PU vs. EC, AV vs. SV was significant. The means on the graph with the same letter indicate no statistical significance between times (Boferroni adjustment, *p*=0.05/18=0.002). Standard error represented by the vertical bars. (Legend: SV – sub-threshold vibration, AV – above-threshold vibration, PU – pitch-up, EC – eyes closed)

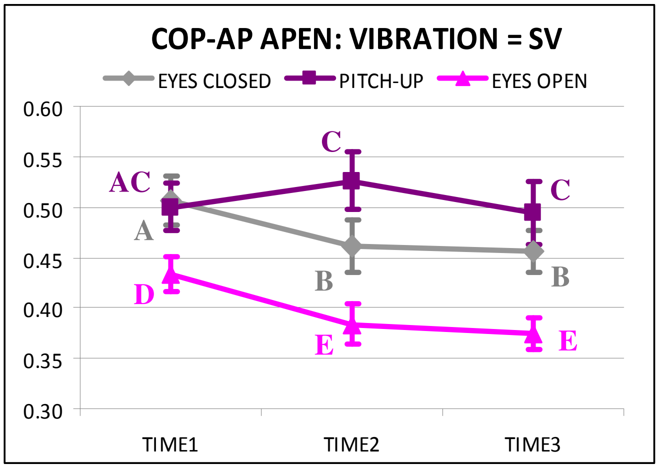


Table 4.6-2: Time*Vision*Vibration for COP and COM RMS and area in the AP and ML directions *p*-value. Highlighted *p*-value shows significant results.

MEASURES	df	Error df	F	p-value
COP-AP RMS	3.7	73.8	5.287	0.001
COP-ML RMS	4	80	3.311	0.015
COP AREA	2.2	43.1	2.995	0.057
COM-AP RMS	3.9	77.4	1.517	0.207
COM-ML RMS	1.9	37.7	0.96	0.388
COM AREA	3.2	64.2	3.586	0.016

Figure 4.6-2: Time*Vision*Vibration for COP AP RMS for pitch-up visual conditions. Contrast for Time1 vs. Time2, Pitch-up (PU) vs. eyes closed (EC), above-threshold (AV) vs. sub-threshold (SV) was significant. Standard error represented by vertical bars. The means on the graph with the same letter indicate no statistical significance between times (Boferroni adjustment, p=0.05/18=0.003)

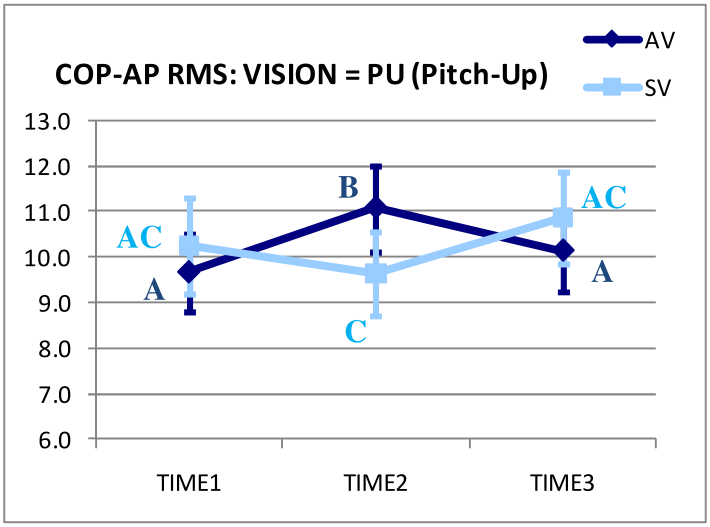
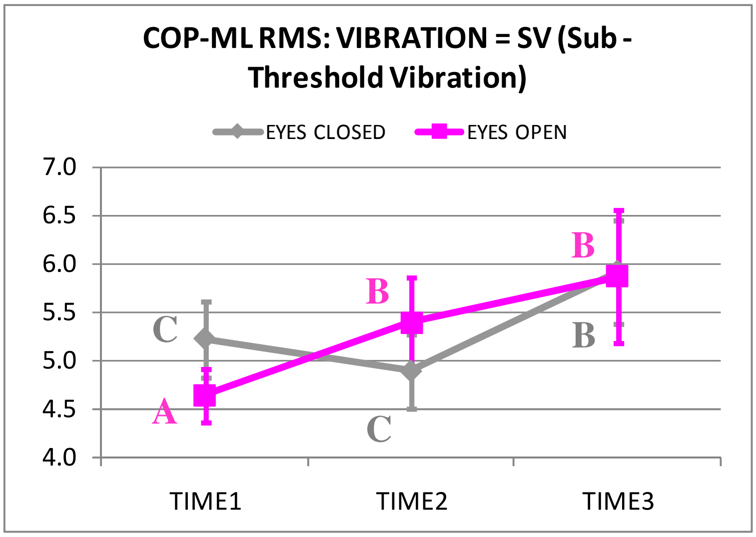


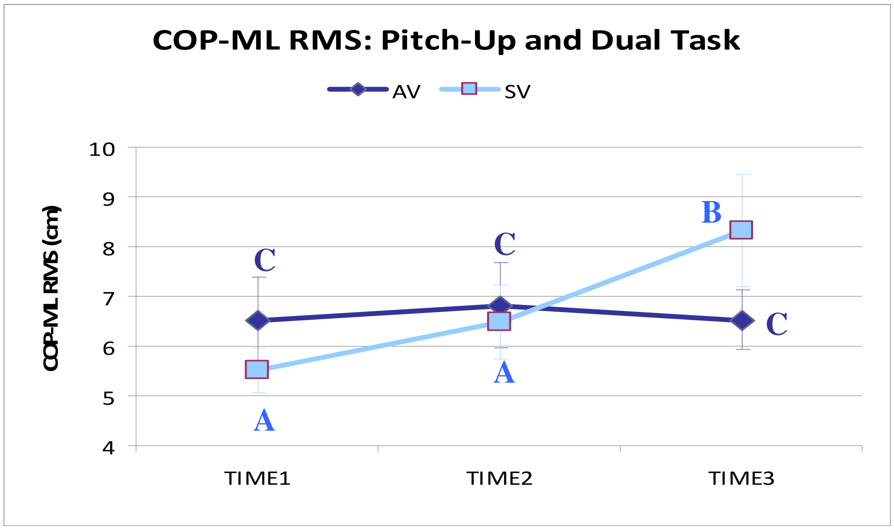
Figure 4.6-3: Time*Vision*Vibration for COP ML RMS for Eyes closed (left) and Eyes open (right) visual condition. Contrast for T1 vs. T2, EO vs. EC, AV vs. SVwas significant. No significant interaction for Time*Vision at vibration level AV. Standard error represented by vertical bars. The means on the graph with the same letter indicate no statistical significance between times (Boferroni adjustment *p*=0.05/18=0.003).



4.7 The Effects of the Interaction between Vibration Noise, Vision, Task and Vibration Level

An interaction between Time*Vision*Vibration*Task was significant for COP-ML RMS [F(2.8,56.5)=3.40, *p*=0.03]. COP-ML RMS response was significant for the interaction between the vibration applied and vibration level (SV vs. AV) when subjected to a pitch-up vision while performing dual task (Figure 4.7-1) . COP-ML RMS increased significantly after SV was removed as compared to before SV application (time 1). The SV applied increased the COP-ML RMS slightly but not significantly. In contrast, AV did not change the COP-ML RMS during and after vibration was applied when compared to pre-vibration.

Figure 4.7-1: Time*Vision*Task*Vibration: COP-ML RMS interaction of sub-threshold and above-threshold vibration with time (pre-vibration, on vibration, and post-vibration) during pitch-up vision and dual task condition. The means on the graph with the same letter indicate no statistical significance between times (Boferroni adjustment) per vibration level. Standard error represented by the vertical bars.



CHAPTER 5

DISCUSSION

5.1 The Effects of Vibratory Noise on the Interaction between Dual Task and Pitch-up Vision on Postural Control and Balance

COP magnitude variability (RMS) in the ML direction increased after the sub-threshold vibration (SV) was removed when the visual condition was challenging (pitch-up) and at the same time performing an attention demanding cognitive task. The application of SV slightly increased the COP ML RMS but it was not significant enough. The added noise might have re-structured the postural response in COP ML but was not pronounced but then when the SV was removed, it made the remaining feedback more pronounced. The result also suggests that the time delay in the effect of the SV on the postural control variability response was caused by the attention capacity involved due to the time needed to process sensory information. However, the application of above-threshold (AV) did not affect COP ML RMS during pitch-up vision and dual task conditions.

5.2 The Effects of Vibratory Noise and Vision on Postural Control and Balance

The applied SV and AV on the plantar foot surface affected the COP regularity and variability differently when subjected to different visual conditions.

SV increased the COP temporal structure regularity (lower ApEn) in the AP direction when visual feedback was removed (eyes closed) or when non-conflicting visual feedback (eyes open) was present. After the SV was removed, the COP AP ApEn regularity maintained its effect on the temporal structure. These results suggest that SV restructured postural control when vision was removed leading to more regular COP fluctuations and may imply more efficient postural control. The effect of SV in postural control may have led to adaptation involved in motor or postural learning. The adaptive mechanisms of the postural control system are thought to be due to the sensory re-weighting causing an increased reliance on the tactile information (Tjernstrom, 2010) or due to postural adaptive learning which is necessary to resolve sensory conflicts. On the other hand, the COP AP ApEn did not change when AV was applied. However, after AV was removed, the COP AP ApEn regularity increased (lower ApEn). This observation suggest that AV may have restructured postural control but was not pronounced but when AV was removed, made the remaining feedback more pronounced that resulted to an increased postural response regularity, thus suggesting adaptive sensory-motor learning.

Nonlinear measures of the structure of motor variability such as ApEn provide insights into the predictability across time. The magnitude and structure of COP variability responds differently to changes in visual feedback and cutaneous sensation. Changes in the COP variability magnitude and structure can be viewed as a result of reorganization of motor output (Hong, 2007). An increase in the postural response time series regularity (decreased ApEn) may be interpreted as an increase in the amount of attention invested in postural control. Somatosensory cortex (S1 and S2) and thalamus activation was shown in a previous study through fMRI during plantar vibrotactile stimulation (Golaszewski et al., 2006; Siedentopf et al., 2008) thus implying increased neuronal activation. The application of SV may have caused enhanced sensory information from the foot thus increased COP regularity (decreased ApEn) was observed which implies an increased reliance on tactile sensory information in postural control and balance.

Removal of visual feedback (eyes closed) and challenging visual feedback (continuous pitch-up visual flow) exhibited a more complex or random COM AP ApEn (higher ApEn) as compared to when a non-conflicting visual feedback was present (eyes open). Regardless on the vibration level (SV or AV) applied, the vibratory noise increased the COM AP ApEn regularity (lower ApEn) during eyes closed and eyes open but not during pitch-up visual condition. For eyes closed and eyes open, the COM AP ApEn regularity maintained its effects even after the vibration was removed. The result suggests that the COM time series data in the AP direction became more structured with the application of the vibration noise. This observation may be explained by a strategy used to maintain a stable human bipedal stance by keeping the COM sway in motion within the base of support (Goodworth, 2010).

The vibratory noise applied did not affect the complexity or randomness of the COP and COM when in a continuous pitch-up visual flow which seem to suggest that pitch-up vision overwhelmed the effect of vibration noise on the postural temporal structure. On the other hand, the magnitude of the variability of COP (RMS) was affected during pitch-up vision when the vibration applied.

COP magnitude variability (RMS) was affected in the AP direction when subjected to a continuous visual field flow (pitch-up). The AV applied increased the COP AP sway variability and then the COP AP sway variability decreased when the vibration was removed. However, SV did not show any effect on the COP AP RMS during pitch-up visual conditions. During pitch-up vision, visual feedback was challenged and resulted in an altered reliance of the vision and somatosensory information used in postural control. The increased in the COP sway magnitude variability suggests that the vibration noise affected postural control and balance by enhancing sensory information through a compensatory adaptation in response to the conflicting visual feedback as opposed to diminished control. Typically, an increase in postural sway is interpreted as a degraded postural control, however considering the pitch-up visual condition presented with altered visual sensory information to postural control system, the increase COP variability with AV may be interpreted as a functional adaptation by a deliberate increase in sway variability magnitude to exploit the somatosensory and vestibular system (Roerdink, 2011). The conflicting visual information caused continuous modulation of postural responses due to the absence of static cues thus would require an adaptive postural control that is most probably at cortical level (Keshner, 2004; Wiesendanger, 1975). An artificial visual flow field stimuli such as the pitch-up vision evoked postural responses and conscious illusion of self-motion (vection) (Dichgans, 1972) and since the perception of self-motion most likely arises from cortical level (Kleinschmidt, 2002), the result of the study suggests that AV applied affected the cortical level of postural control particularly during pitch-up visual condition requiring postural re-stabilization. On the other hand, SV effects on postural responses to eyes open and eyes closed conditions only, suggests that SV would affect subcortical level of postural control.

The results of the effects of the different vibration levels (SV and AV) during challenging visual flow with AV increasing postural variability through an increase in COP AP RMS was in agreement with the hypothesis. SV was able to increase postural response regularity (lower ApEn) during eyes open and eyes closed but not during pitch-up visual conditions.

5.3 The Effects of Vibratory Noise and Attention Demanding Task on Postural Control and Balance

The application of vibration affects the COM postural response by decreasing COM AP ApEn complexity (lower ApEn) only when performing a dual task while no changes were seen when just standing quietly (single task). The effect of vibration during dual task was retained even after the vibration was removed where COM time series in AP direction decreased in complexity or randomness as a post effect of the vibratory noise applied. On the other hand, COM ML ApEn decreased its complexity (lower ApEn) when vibration was applied and after vibration was removed regardless of whether performing a single or dual task. Previous studies suggest that ApEn measures may be used as a marker to the amount of attention invested in postural control. Dual tasks have been shown to have an increased complexity or randomness (higher ApEn) as compared to single task (postural task alone) (Cavanaugh, 2007; Donker, 2007; Stins, 2009). In line with other research (Stins, Michielsen, Roerdink, & Beek, 2009) , the results of this study showed that COM randomness and complexity increased (higher ApEn) when attention was diverted from postural control which is in agreement with previous studies. The decrease in COM AP complexity (lower ApEn) with vibration suggested that the application of vibration increased the amount of attention invested in postural control or balance when performing an attention demanding cognitive task. Increased entropy was seen when subjects performed a secondary cognitive task (Cavanaugh et al., 2007; Donker et al., 2007) which was also demonstrated in this study (Figure 4-1-3).

Though it was hypothesized that the effect vibration noise with the dual task would increased regularity (lower ApEn) of the postural response for sub-threshold vibration and increase variability (increase RMS) of postural response for above-threshold vibration, this was not the case. Both sub-threshold and above-threshold vibration levels increased regularity when vibration was applied while performing a dual task while COP and COM magnitude variability did not show any effect of vibration with dual task conditions. Thus both SV and AV have the same affect, both increased the attention to postural control of the COM response.

5.4 The Main Effects of Vibratory Noise on Postural Control and Balance

Both COP and COM ApEn in the ML direction became more regular (lower ApEn) when vibration noise was applied regardless of the vision, task, and vibration level (SV or AV) conditions. At the same time, COM RMS in the AP and ML direction increased when vibration noise was applied regardless of the vision, task, and vibration level (SV or AV) conditions. The effects of vibration noise were maintained for these measures after the vibration noise was removed. These results were consistent with the preliminary study conducted where vibration noise affected postural response by becoming more variable and more regular (Appendix D). The immediate after effect of the vibration applied suggest sensory-motor learning.

5.5 Conclusion

Posture and balance were affected by the application of vibration noise to facilitate postural control in relation to vision and level of attention. Cognitive functioning and control of posture and balance are related to some extent (Andersson, Hagman, Talianzadeh, Svedberg, & Larsen, 2003). Postural control has been observed to involve either automation, cognition, or both. Dual task paradigms have been found to impair posture control due to the divided allocation of attention. The vibration noise enhanced the amount of attention invested in postural control while performing an attention demanding cognitive task and sensory-motor learning was achieved by increasing COM sway structure regularity but not the COM sway magnitude. These results suggest that the interaction between vibration noise and dual task resulted in the re-organization of the postural control system without affecting the equilibrium region for the COM sway excursion (Tjernstrom,2010).

Vibration noise facilitates postural control in relation to vision by increasing postural response regularity or by increasing postural response variability. For COM, only postural response regularity but not sway variability was affected by vibration noise in relation to vision regardless of the vibration level (SV or AV). On the other hand, for

COP postural responses, the effect of SV and AV differs. Due to the perception of self-motion from the pitch-up visual condition, COP postural response most likely arises from cortical level. Since AV only affected COP responses during pitch-up visual condition and not SV, this study suggests that above-threshold vibration applied affected the cortical level of postural control. While SV effects on postural responses to eyes open and eyes closed conditions only suggests that SV would affect subcortical level of postural control.

5.6 Future Directions

Having completed this research, there were interesting results that will help steer future research. The results provide the scientific basis that is needed to develop useful SR-based rehabilitation device or prostheses for people with sensory information and processing deficiency like aging or stroke. It will also be interesting to study whether the SR-based device such as the vibrating footwear can also be effective in improving gait and preventing falls during surface perturbations. This study's findings on the after effects of vibratory noise can be used to determine dosage of vibrotactile stimulation in the design of vibrating footwear.

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APPENDICES

APPENDIX A

FILAMENT EVALUATION TEST

Subject ID: ________________________________ Date: ____________

Sensory Testing with Filaments : Subject is asked to close his/her eyes and let the tester know when, where and what kind sensation did she/he feel, if she/he felt any when the tester touches the monofilament on lateral foot and great toe.

Lateral Foot

Right: ____ 6.10 ____ 5.07 ____ 4.17
Left: ____ 6.10 ____ 5.07 ____ 4.17

Great Toe
Right: ____ 6.10 ____ 5.07 ____ 4.17
Left: ____ 6.10 ____ 5.07 ____ 4.17

Vibration Test (heel of foot) : Subject is asked to close his/her eyes and a vibrating tuning fork is placed on the heel of the foot. The subject is expected to respond about the kind of sensation and where it is felt.

Right: Yes No

Left: Yes No

Sensory (sharp point) : Subject is asked to close his/her eyes and made him/her feel comfortable and the tester touches the pin prick on lateral foot and great toe. The same quality of prick is used. The subject is expected to respond about the kind of sensation and where it is felt.

Lateral Foot	*Great Toe*
Right: Yes No	Right: Yes No
Left: Yes No	Left: Yes No

APPENDIX B

CENTER OF PRESSURE

Center of Pressure Formula (NeuroCom Research Module, 2007)

$$COF(x) = \left[\frac{F_{zL} * (X_L - 4.5) + F_{zR} * (X_R + 4.5)}{F_{zL} + F_{zR}} \right]$$

$$COF(y) = \left[\frac{F_{zL} * Y_L + F_{zR} * Y_R}{F_{zL} + F_{zR}} \right]$$

Where:

$COF(x)$ = The total COF X components (in units of inches) in the total coordinates

$COF(y)$ = The total COF Y components (in units of inches) in the total coordinates

X_L = The COF X component on Left force plate in local coordinates calculated in Left/Right Center of Force (COF) Calculation session

X_R = The COF X component on Right force plate in local coordinates calculated in Left/Right Center of Force (COF) Calculation session

Y_L = The COF Y component on Left force plate in local coordinates calculated in Left/Right Center of Force (COF) Calculation session

Y_R = The COF Y component on Right force plate in local coordinates calculated in Left/Right Center of Force (COF) Calculation session

F_{zL} = The vertical force on the Left force plate

F_{zL} = The vertical force on the Right force plate

APPENDIX C

PROTOCOL

TRIAL NO	SURFACE	TASK	VIBRATION LEVEL	VISION	TIME
1	FOAM	SINGLE TASK	SUB-THRESHOLD	EYES-CLOSED	90
2	FOAM	SINGLE TASK	SUB-THRESHOLD	EYES-OPEN	90
3	FOAM	SINGLE TASK	SUB-THRESHOLD	PITCH-UP	90
4	FOAM	SINGLE TASK	ABOVE-THRESHOLD	EYES-CLOSED	90
5	FOAM	SINGLE TASK	ABOVE-THRESHOLD	EYES-OPEN	90
6	FOAM	SINGLE TASK	ABOVE-THRESHOLD	PITCH-UP	90
7	FOAM	DUAL TASK	SUB-THRESHOLD	EYES-CLOSED	90
8	FOAM	DUAL TASK	SUB-THRESHOLD	EYES-OPEN	90
9	FOAM	DUAL TASK	SUB-THRESHOLD	PITCH-UP	90
10	FOAM	DUAL TASK	ABOVE-THRESHOLD	EYES-CLOSED	90
11	FOAM	DUAL TASK	ABOVE-THRESHOLD	EYES-OPEN	90
12	FOAM	DUAL TASK	ABOVE-THRESHOLD	PITCH-UP	90

APPENDIX D

PRELIMINARY STUDY (PROPOSAL)

Sensory information from the plantar foot surface contributes to human postural control and stability where loss of sensory information could lead to impaired balance thus increasing the probability of falls. Previous studies have shown that the application of noise in a system can enhance signal detection and human postural stability. The preliminary study was conducted to analyze and understand how vibratory noise applied on the plantar foot surface affects the human posture. To better understand these effects, can we use non-linear measure such as ApEn to detect subtle movement variability in postural responses due to vibration applied?

The objective of this preliminary study is to analyze the effects of the vibratory noise on the responses of postural control. To be able to study the effect of the vibratory noise on posture, the goal is to design and develop a vibrating footwear. The study also aims to explore the use ApEn to quantify changes in postural responses.

Based on the literature reviewed, the loss of sensory information can impair postural stability and balance control. Standing on a compliant surface (foam) will reduce sensory input on the plantar foot surface causing an increase in postural response. It was hypothesized that vibratory noise applied to plantar foot surface alter posture and balance control through stochastic resonance. It was also hypothesized that non-linear measures such as ApEn will be able to detect subtle changes in postural response that are undetectable by linear sway measures.

D.1 METHODOLOGY

D.1.1 Subjects

Seven healthy adults (2 women and 5 men; age range 18-30 years old) participated in this study. All subjects have a minimum of 20/40 corrected vision in each eye and have adequate hearing to listen to Investigator's instructions from across the room. All subjects have no history of central or peripheral neurological disorders or problems related to movements of the spinal column (e.g., significant arthritis or musculoskeletal abnormalities), and have given informed consent.

D.1.2 Apparatus and Instrumentations

Three vibrating elements, coin-shaped DC vibrating motors (diameter 8.0 ± 0.05 mm and 3.40mm thick), were embedded (two on the forefoot and one on the heel) in each shoe (i.e. flip-flops). Each element received a random pulse signal, generated by MATLAB (version 7.11.0, The MathWorks Inc., Natick, Massachusetts) and sent to the data acquisition board (NI DAQ PCI 6259) to turn the elements on and off, thus generating vibratory noise stimulation on the plantar foot surface at a frequency of approximately 10 to 55 Hz. The amplitude of the signal was controlled independently for each vibrating element with a potentiometer (10K-Ohm wheel, 0.5W). The potentiometers were adjusted for each subject until the vibration stimulus was at the subject's threshold level (i.e., vibration is just noticeable). The stimulation level was then set to 90% of the threshold level for sub-threshold vibration stimuli for each subject.

D.1.3 Procedures

Prior to any testing, subjects will be provided with the Subject Information and Consent form. They were given ample time to read it and the opportunity to ask and receive answers to any questions they may have. Testing will proceed only after subjects are comfortable that they understand the form and have signed it.

At the beginning of the test session, a filament evaluation test was conducted to include or exclude a subject. A filament evaluation test (See Appendix A) was conducted to determine the level of sensation of the subject's feet using a 10-g Semmes-Weinstein Monofilament (SWM) on the great toe and lateral side of the foot for both left and right feet. Subjects were tested with the 10-g SWM using three filament sizes 4.17, 5.07 and 6.10. The SWM exerts 10 grams of force when bowed into a C-shape against the skin for one second. Subjects were excluded if sensation on the plantar surface of the feet was absent when tested with the largest filament. All seven subjects in this study passed the filament test and no one was excluded.

To test for the vibrotactile sensitivity, a 128Hz tuning fork was applied perpendicularly with constant pressure on the heel of each foot. The subjects reported whether the tuning fork was vibrating. The vibrotactile sensitivity test was used to determine if the subject was able to differentiate the sensation of vibration from that of pressure from the contact of the tuning fork.

Subjects were instructed to put on the vibratory footwear and to stand comfortably and maintain an erect posture while standing on a flat surface or on dense foam with eyes closed. The test was conducted on a quiet and darkened room and the sequence of the stimuli was presented randomly.

A NeuroCom (NeuroCom International Inc., Clackamas, Oregon) force plate platform was used to collect the forces and COP data during the test. Motion on the platform will be controlled by the computer and ground reaction forces will be collected to calculate COP. A dense foam (6.5 cm thick) surface was used to create a sensation of instability.

Kinematic data (time and marker positions) were collected from 34 infrared markers placed on the subject's head and body and captured by a motion analysis system Cortex (Motion Analysis Corp., Santa Rosa, California). Subjects' identities cannot be obtained from this system which is only sensitive to infrared signals. All results were identified by subject number and not identified by name. Subjects were given periodic rest breaks to avoid fatigue.

The protocol consisted of a total of 8 trials that lasts for 65 seconds per trial. Each trial has different stimulus conditions based on; surface (hard surface (HS) or dense foam surface (FS)) and vibration level; no vibration (NV), above-threshold vibration (AV) or sub-threshold vibration (SV)). The sequence of the stimuli was presented randomly.

D.1.4 Data Collection and Analysis

The RMS and range for the following outcome measurements: COM, COP, kinematic angles for ankle, knee, and hip and trajectory ellipse area over the 65 seconds period trials were used. The COM, COP and Kinematic Angles data were all in the anterior-posterior plane. All data collected were processed using MATLAB.

D.1.4.1 Center of Mass

Kinematic data from the infrared markers and motion analysis system were collected and the whole body center of mass excursions were computed with reference to anthropometric data (Winter, 1990). The marker data were collected at 120Hz and low-pass filtered using fourth order Butterworth filter with a cut-off frequency of 4Hz. The data were then normalized by subtracting their initial position.

D.1.4.2 Center of Pressure

COP is the point of vertical ground reaction force vector that represents a weighted average of all the pressures over the surface of contact with the platform. The COP data were collected using the NeuroCom Research Module. The NeuroCom Research Module has two independent force plates (left and right) and each force plate measures three forces (Fx, Fy, Fz) and three moments (Mx,My,Mz) and calculates the total COP (Appendix B). The force plate data were sampled at 200Hz and then normalized against the subject's initial position

D.1.4.3 Ankle, Knee, and Hip Angular Excursion

The ankle, knee, and hip segmental angles were computed using two vectors in the sagittal plane over the 65 seconds trial period using MATLAB routines (Christoph Reinschmidt Matlab®). The segmental angle data were normalized against the subject's angle data at time zero.

D.1.4.4 Ellipse Area

The COP and COM excursions in the AP and ML directions were analyzed by computing the area of excursion using principal component analysis (PCA). In this method, the area of excursion was estimated by fitting an ellipse to the COP and COM covariance matrix data to include 85% of the data points. The two main axes of the ellipse were found by calculating the eigenvalues of the covariance matrix between the AP and ML data (Duarte & Zatsiorsky, 2002; Latash, Ferreira, Wieczorek, & Duarte, 2003). The first eigenvector of the covariance matrix is the direction of the principal axis and the corresponding largest eigenvalue is the variance along this axis. The second eigenvector which is orthogonal to the first eigenvector defines the direction of the minor axis and the corresponding eigenvalue is the variance along this axis (Oliveira, Simpson, & Nadal, 1996).

D.1.4.5 Approximate Entropy

Research and analysis on recently developed family of formulas and statistics suggests that ApEn can classify complex systems given at least 1000 data values in diverse settings that include both deterministic chaotic and stochastic processes (Pincus, 1991). ApEn was calculated to determine the unpredictability of the time series of the COP and center of mass excursions. To calculate ApEn for a time series containing N data points, $u(1), u(2), u(3), \ldots u(N)$, two parameters were chosen, r and m. The r parameter defines the error tolerance and the m parameter defines the pattern length. Sequence of vectors $x(1), x(2), \ldots x(N-m+1)$ were defined by $x(i) = [u(i), u(i+1), \ldots, u(i+m-1)]$. Second step was to define the $d[x(i), x(j)]$ for vectors $x(i)$ and $x(j)$.

$$d[x(i), x(j)] = \max(|u(i+k-1) - u(j+k-1)|), \quad k = 1,2,\ldots m$$

The third step was to find the $C^m_i(r)$ values which measures (within the tolerance r) the regularity of patterns similar to a given pattern of window length m for each i, $1 \leq i \leq N - m - 1$.

$$C^{m}_{i}(r) = (\text{number of j such that } d[x(i), x(j)] \leq \text{r})/(N - m + 1)$$

The fourth step was to define $\Phi m(r)$ as the average value of the natural logarithm of $C^{m}_{i}(r)$. Lastly, ApEn is calculated as

$$\text{ApEn}(m,r,N) = \Phi m(r) - \Phi m{+}1\ (r)$$

ApEn results in a unit-less value from 0 to 2 where smaller values of ApEn imply greater probability of repeating sequences of *m* observations.

The ApEn values were calculated for the AP components of COP and COM over the test duration (N=13000) from each trial. The parameters used for *r, m* and lag were 0.2, 2 and 10 respectively that were chosen based on previous works (Cavanaugh et al., 2005; Cavanaugh et al., 2007; Dusing et al., 2009; Pincus, 1991).

D.1.5 Statistics

The effects of the vibration study on the healthy young adults' postural organization were tested for its statistical significance using two-way repeated measures analysis of variance (ANOVA) to test the hypotheses. The main effect of the vibration with three levels: no vibration (NV), above-threshold vibration (AV), and sub-threshold vibration (SV) and surface with two levels (hard vs. foam) on postural sway measures and whether interactions between the vibration and surface at 95% confidence level ($p<0.05$). Bonferroni confidence interval adjustment was used to compare the main effects. IBM SPSS Statistics (version 19, IBM Corporation, Somers, New York) program was used for all statistical analyses.

D.2 RESULTS

D.2.1 COP and COM Responses

The COP, COM responses (RMS, range and ellipse area), and ankle angles exhibited significant differences (Table D-1) on vibration. After post hoc analysis, responses between no vibration (NV) and sub-threshold vibration (SV) stimuli were significant (Table D-2) except for ankle angle and a marginal COM RMS ($p=0.051$) with SV producing a greater response in the AP direction than the NV condition (Table D-3). Significant responses were also seen between NV and AV but only for COM in the AP direction for range and ellipse area with marginal RMS ($p=0.054$) producing greater response in AV (Table D-3) as compared to NV condition. No significant difference was found between SV versus AV. There was no significant interaction between the vibration and surface groups Figure D-1 is a record of COP in the AP direction for a subject in a quiet stance with eyes closed on a force platform subjected to no vibration (NV), sub-threshold vibration (SV), and above-threshold vibration (AV). An example shown in Figure D-2 of the COM's Ellipse areas of the same subject while standing on a hard and foam surface during different vibration. It is evident in these graphs the increase in postural response with vibration applied.

The COP and COM RMS, range, and ellipse area values did not show significant differences between the hard vs. foam surface (Figure D-2). Foam surface COP and COM responses also significantly increased in sway in the ML direction ($p<0.05$). For the ML direction the subjects has larger responses on the foam surface COP ($p= 0.0016$) and COM ($p= 0.015$) RMS compared to hard surface.

Table D-1. *p*-Values of the Main Effects using Two-Way Repeated Measures ANOVA between Vibration Level Group (No Vibration vs. Above-Threshold Vibration vs. Sub-Threshold Vibration) and Surface (Hard vs. Foam)

Measures		Vibration (*p*)	Surface (*p*)	Interaction (*p*)
COP	RMS	0.008*	0.968	0.201
	Range	0.002*	0.464	0.403
	ApEn	0.004*	0.008*	0.831
COM	RMS	0.013	0.623	0.626
	Range	<0.001*	0.177	0.085
	Ellipse Area	0.001	0.112	0.156
	ApEn	0.361	<0.001*	0.272
Angles	Ankle	0.014*	0.009*	0.546
	Knee	0.161	0.908	0.552
	Hip	0.372	0.176	0.481

** $p<0.05$ is statistically significant. SD – standard deviation, NV – no vibration, AV – above-threshold vibration and SV – sub-threshold vibration level.*

Table D-2. p Value of Pair-wise Comparisons of the Vibration Level Group (No Vibration vs. Above-Threshold Vibration vs. Sub-Threshold Vibration)

Measures		NV vs SV *(p)*[a]	NV vs AV *(p)*[a]	SV vs AV *(p)*[a]
COP	RMS	0.030*	0.156	0.103
	Range	0.009*	0.131	0.181
	ApEn	0.004*	0.994	0.285
COM	RMS	0.051[b]	0.054[b]	0.21
	Range	0.015*	0.028*	0.117
	Ellipse Area	0.015*	0.002*	0.236
Angles	Ankle	0.088	0.181	0.734

** $p<0.05$ is statistically significant. NV – no vibration, AV – non-threshold vibration and SV – sub-threshold vibration level.*

[a] *Adjustment for multiple comparisons: Bonferroni*

[b] *p value is marginal*

Table D-3. Mean and standard deviation values of the COP, COM, Angles, Ellipse Area ApEn values on different vibration stimulus

Measures		No Vibration	Sub-threshold Vibration	Above-threshold Vibration
COP	RMS*	0.56 ± 0.16	0.96 ± 0.42	0.77 ± 0.28
	Range*	2.96 ± 0.87	4.9 ± 2.08	1.54 ± 1.54
	ApEn	0.44 ± 0.11	0.36 ± 0.13	0.41 ± 0.13
COM	RMS*	0.43 ± 0.12	0.73 ± 0.33	0.60 ± 0.01
	Range*	12.18 ± 0.61	3.49 ± 1.27	2.78 ± 1.00
	Ellipse Area**	0.91 ± 0.63	3.24 ± 2.67	2.34 ± 1.73
	ApEn	0.34 ± 0.11	0.3 ± 0.13	0.31 ± 0.11
Angles***	Ankle	0.52 ± 0.41	0.98 ± 0.78	0.78 ± 0.58
	Knee	0.57 ± 0.42	1.21 ± 1.14	0.88 ± 1.06
	Hipc	0.86 ± 0.41	1.3 ± 1.48	2.66 ± 5.12

**values are in centimeters*

***values are in centimeters squared*

****values are in degrees*

Figure D-1. COP in AP direction for a subject standing quietly with eyes closed on a hard surface (top) and foam surface (bottom) over the 65 seconds trial period. The graphs show the COP excursions during no vibration (NV), sub-threshold vibration (SV), and above-threshold vibration (AV)

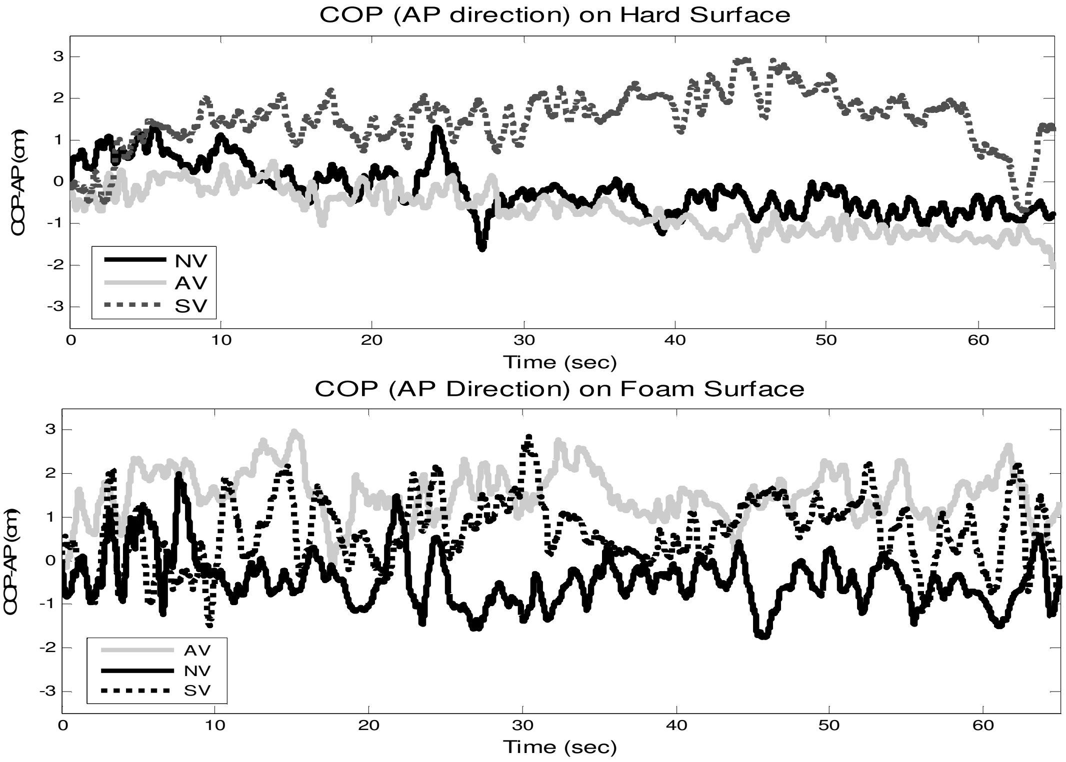


Figure D-2. COM Ellipse area at 85% confidence level for a subject standing quietly on hard and foam surface over 65 seconds trial period during NV (top left), SV (top right), and AV (bottom left). The ellipses fitted on the covariance matrix data includes about 85% of the data points. The two main axes of the ellipse are the eigenvalue of the covariance matrix between the AP and ML data

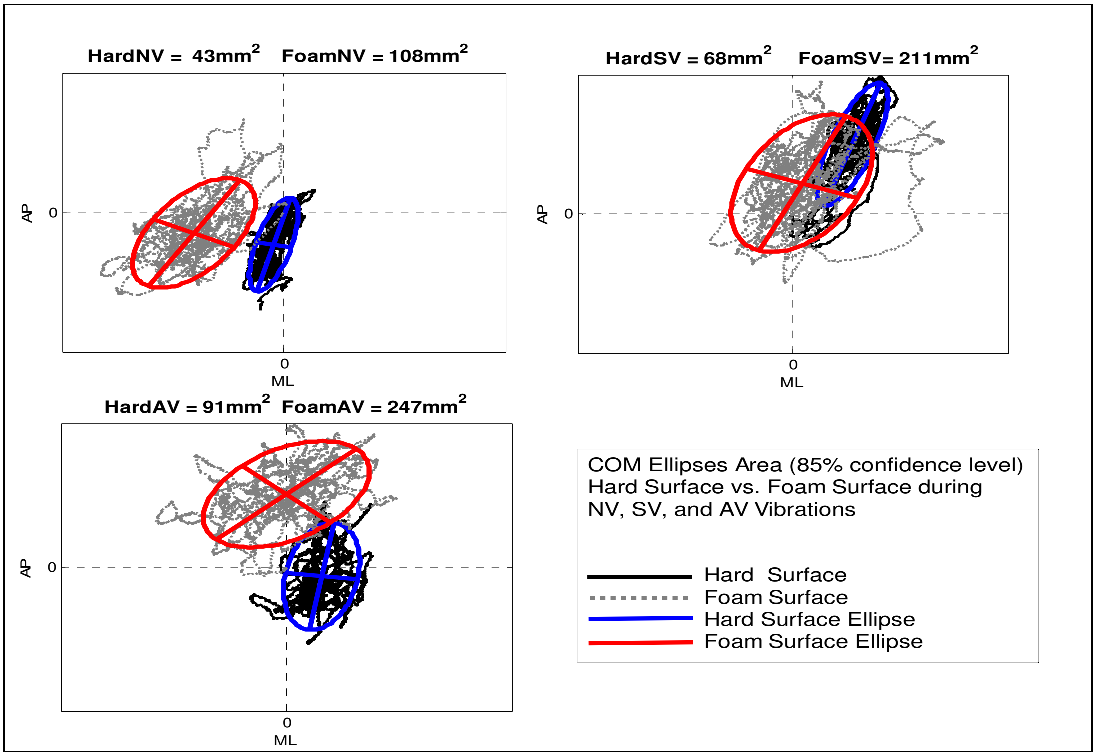
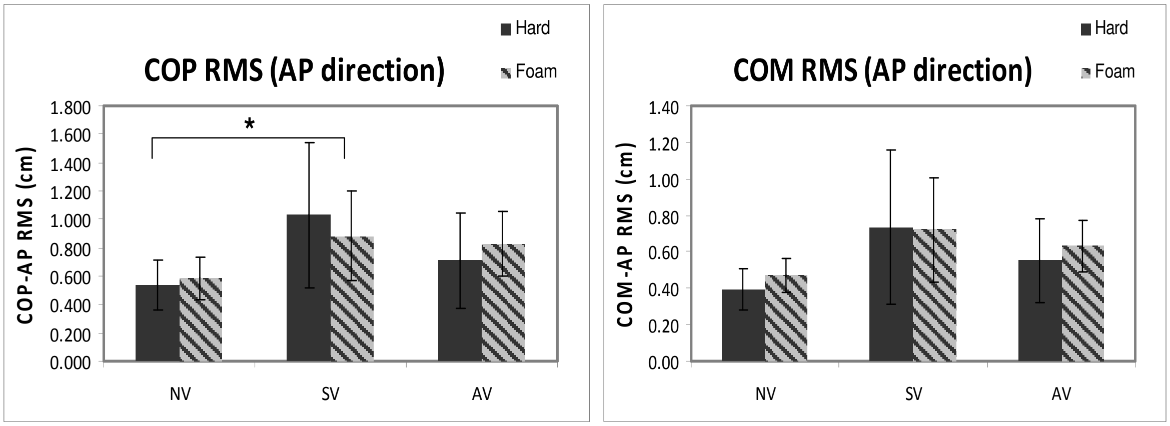


Figure D-3. RMS values for COP (left) and COM (right) in the anterior-posterior (AP) direction for all trials between surface group (Hard and Foam) and the Vibration level group: No vibration (NV), sub-threshold vibration (SV) and above-threshold vibration (AV) in healthy adults (n=7). For each group, the value is the group average



* *$p<0.05$ is statistically significant*

D.2.2 COP and COM ApEn

Figure D-4 shows the ApEn values for COP and COM in the AP direction. The figure plotted the average of the ApEn values for each surface (hard and foam) across the vibration level group (NV, SV, and AV). The COP and COM ApEn values generally decline with vibration applied compared to NV. But only COP ApEn showed significance *($p=0.014$)* with vibration (Table D-1). Post hoc analysis (Table D-2) showed that COP ApEn was only significant between NV vs. SV *($p=0.004$)* where ApEn value decreased with SV applied (Table D-3). When sub-threshold vibration was applied, COM and COP ApEn values decreased compared to when there was no vibration thus becoming more deterministic or less chaotic. The prominent feature is that when subjects were standing on a foam surface has higher ApEn than on hard surface. Despite the COM and COP RMS, range and ellipse area values not showing any significant results between the hard and foam surfaces, the ApEn values were able to show statistical significance for both COP (p=0.008) and COM (p<0.000). ApEn values for COP and COM became more random (higher ApEn values) on foam surface than on hard surface (Figure D-4).

Table D-4 shows the coefficients of Pearson correlation between the RMS, ankle angles, and ApEn of the COP. Ankle angles and RMS were found to be positively correlated as expected for both foam and hard surface. Examining the correlation of the variability of postural response by linear (RMS) and nonlinear (ApEn) means, between the surface (hard and foam), RMS was observed to be negatively correlated with the ApEn. Therefore, as the variability of the COP displacement is increased, the complexity of the system decreased. But this relationship was only found to be significant for the hard surface condition.

D.2.3 Ankle, Knee, and Hip Angular Excursion

No significance was found in the knee and hip angular excursion between surface and vibration levels. Ankle angular excursion on the pitch plane showed significance (Table D-1) between the hard and foam surface. The foam surface caused the subject to either extend or flex more on the ankle when standing on the foam surface (Table D-3). Post hoc analysis on the ankle angular excursions however on the vibration level group showed no significance.

Figure D-4. Approximate Entropy values for COP (left) and COM (right) in the anterior-posterior (AP) direction for all trials between surface group (Hard and Foam) and the Vibration level group: No vibration (NV), sub-threshold vibration (SV) and above-threshold vibration (AV) in healthy adults (n=7). For each group, the value is the group average

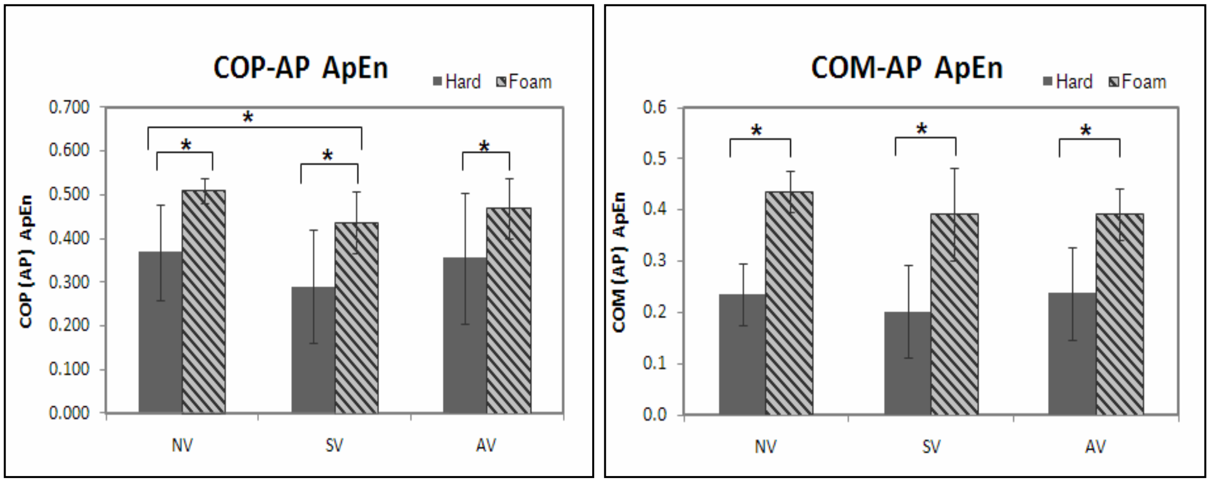
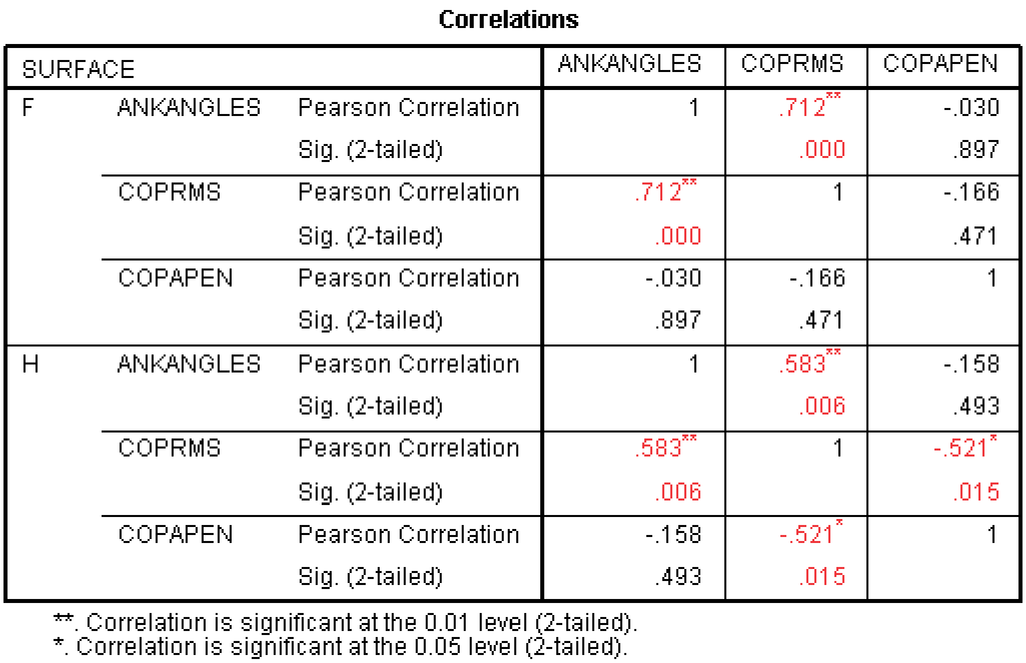


Table D-4. Two-tailed Pearson correlation coefficients between the means of RMS, ApEn and ankle angles of center of pressure in anterior-posterior direction



Correlations

SURFACE			ANKANGLES	COPRMS	COPAPEN
F	ANKANGLES	Pearson Correlation	1	.712**	-.030
		Sig. (2-tailed)		.000	.897
	COPRMS	Pearson Correlation	.712**	1	-.166
		Sig. (2-tailed)	.000		.471
	COPAPEN	Pearson Correlation	-.030	-.166	1
		Sig. (2-tailed)	.897	.471	
H	ANKANGLES	Pearson Correlation	1	.583**	-.158
		Sig. (2-tailed)		.006	.493
	COPRMS	Pearson Correlation	.583**	1	-.521*
		Sig. (2-tailed)	.006		.015
	COPAPEN	Pearson Correlation	-.158	-.521*	1
		Sig. (2-tailed)	.493	.015	

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

D.3 DISCUSSIONS

The results of this study showed that the application of sub-threshold vibratory noise significantly affected the COP and COM causing larger excursions than during no vibration but with increased regularity (lower ApEn). Thus the increased in variability coupled with the regulated response indicates a strategy of control to make appropriate adjustment to maintain balance (Harbourne & Stergiou, 2009) which implies a more controlled stabilization. This result contrasts with previous findings where reduced sway parameters were observed with sub-threshold vibrations applied (Priplata et al., 2003; Priplata et al., 2006). On the other hand, Hijmans et. al (2008) found no effects of sub-threshold vibration in non-disabled subject. Increased postural sway measures resulting from the application of sub-threshold vibratory noise may imply decreased postural control, however smaller postural sway measures may indicate the subject's locking of joints thus limiting their sway to improve stability. For example, measuring the excursions like COP during quiet stance can be interpreted in two ways. Hughes *et. al.* (1996) study defined increased postural sway measure (ellipse area) as having greater postural control, whereas Riach and Hayes' (1987) study defined it otherwise.

One may interpret variability as a sign of poor balance and deficient postural control, but on the other hand, variability may be interpreted as a characteristic of a successful vigilant strategy to keep balance. Measures such as entropy (i.e. ApEn) applied to biological signals are expected to reflect the state or complexity of the biological system (Borg & Laxaback, 2010). ApEn decreased with the applied sub-threshold vibration. A decrease in ApEn may be interpreted as an increase in the amount of attention invested in postural control where increased entropy were seen when subjects performed a secondary cognitive task (Cavanaugh et al., 2007; Donker et al., 2007) or may reflect as a means of behavioral flexibility as dancers have been shown to have lower entropy as compared to non-dancers (Schmit, Regis, & Riley, 2005). Previous studies showed that an activation of the somatosensory cortex (S1 and S2) and thalamus were observed through fMRI during plantar vibrotactile stimulation (Golaszewski et al., 2006; Siedentopf et al., 2008) thus increasing tactile attention. The application of sub-threshold vibration may have caused enhanced sensory information from the foot thus increasing tactile attention was observed with the decreased COP ApEn. The low-level vibration noise resulting in increased regularity in the COP trajectories (lower ApEn) may be interpreted as an increase in the regularity of postural response due to the decreased of unnecessary variability and complexity of the system to increase automaticity or efficiency of postural control.

The common expectation is to find lesser postural sway with the application of sub-threshold vibration in general. In this case, the result shows the opposite. The subjects were all healthy and do not have any problems in foot sensation (touch, vibration or position) and do not have any balance issues. The sensorimotor alterations observed might be induced by the modifications of the cutaneous sensory messages (Ribot-Ciscar, Vedel, & Roll, 1989). Thus the results suggest that the sub-threshold vibration enhances the vibration sense causing re-weighting in sensory cues in postural control. What's interesting is that both COP and COM showed significant differences on postural measures during sub-threshold vibration compared to control but only COM measures were found to be significant when vibration was above threshold level. The changes observed suggest that vibration contributed to the reallocation of attention in postural control. That AV may have decreased cortical activation yielding less tactile attention thus less COP response. This observation suggests that the different level of vibration may have affected postural control differently. This findings could be attributed to the sensory re-weighting where the CNS dynamically and selectively adjust the sensory inputs in postural control as conditions change (Oie, Kiemel, & Jeka, 2002; Peterka, 2002; Peterka & Loughlin, 2004; Vuillerme & Pinsault, 2007). This result supports the phenomena of stochastic resonance where low level noise can significantly enhance tactile sensitivity (Collins et al., 1996; Khaodhiar et al., 2003; Priplata et al., 2006) by increasing signal detection from the plantar surface of the foot even when the person was unaware of the vibration.

The result in this study showed no significance changes on the COP RMS and range with respect to surface compliance. However changes in the ankle angular displacement and ellipse area were seen. These results are in agreement with other studies (Chiang & Wu, 1997; Palluel, Nougier, & Olivier, 2010; Wu & Chiang, 1996). The increase in the ankle angle displacement and ellipse area may imply that the subject increases sway to increase the pressure input for them to reach the tactile threshold level. The foam surface may decrease the reliability of the sensory input of the plantar foot area and proprioceptive sensors. The decrease in the sensory inputs may be because of the reduced pressure under the subject's feet was while standing on foam surface. The ApEn was also able to detect the changes in the COP and COM variability between the hard and foam surface that were not detected by RMS and range measures (Cavanaugh et al., 2007). The randomness (higher ApEn) of the COP oscillations suggests that postural task becomes more difficult when standing on the foam surface as compared to a hard surface due to the decrease in sensory input. Higher ApEn may reflect the information gathering behavior due to sensory deprivation by increasing movement variability. The increased in randomness (higher ApEn) in foam surface might suggest an increase in cognitive involvement in this setting. Increase in cognitive involvement may have compensated for the lack of sensory information that resulted from the reduced pressure detected on the foot when standing on the foam surface. Borg et. al. (2010) study found elderly to have greater entropy versus young adults. The higher ApEn seen in foam surface could be inferred the same way as an effect of a more impaired tactile sensory input. This results is in agreement with other studies where standing on foam surface results in greater entropy than on a rigid surface (Borg & Laxaback, 2010; Santarcangelo et al., 2009; Schmit et al., 2005).

In conclusion, the results of the study show that the addition of sub-threshold vibratory noise to the tactile system, even when the subjects were unaware of the vibration, shows significant effects on postural control and balance. This result supports the hypothesis that stochastic resonance phenomena enhanced somatosensory system information processing. Response differences with above threshold stimulation indicate that the effect of stochastic resonance on posture control is more effective at a sub-cortical level than with cortical attention. The result shows a possible interpretation of the continued exploration of ApEn as a measure to the subtle changes in postural control of commonly used sway measures as applied to the changes of base support in quiet stance. The study also strengthened the hypothesis that the ApEn was a reliable measure for detecting movement variability to the postural system that postural sway measures such as RMS and displacement range were not able to detect.

APPENDIX E

IBM SPSS STATISTICS SYNTAX

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    *Last Updated: June 30 , 2011
    *Repeated Measures ANOVA

    *Restructuring Data (Wide Format)

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        GLM COPAREAT1.EC.DT.AV COPAREAT1.EC.DT.SV COPAREAT1.EC.ST.AV
COPAREAT1.EC.ST.SV
        COPAREAT1.EO.DT.AV COPAREAT1.EO.DT.SV COPAREAT1.EO.ST.AV
COPAREAT1.EO.ST.SV
        COPAREAT1.PU.DT.AV COPAREAT1.PU.DT.SV COPAREAT1.PU.ST.AV
COPAREAT1.PU.ST.SV
        COPAREAT2.EC.DT.AV COPAREAT2.EC.DT.SV COPAREAT2.EC.ST.AV
COPAREAT2.EC.ST.SV
        COPAREAT2.EO.DT.AV COPAREAT2.EO.DT.SV COPAREAT2.EO.ST.AV
COPAREAT2.EO.ST.SV
        COPAREAT2.PU.DT.AV COPAREAT2.PU.DT.SV COPAREAT2.PU.ST.AV
COPAREAT2.PU.ST.SV
        COPAREAT3.EC.DT.AV COPAREAT3.EC.DT.SV COPAREAT3.EC.ST.AV
COPAREAT3.EC.ST.SV
        COPAREAT3.EO.DT.AV COPAREAT3.EO.DT.SV COPAREAT3.EO.ST.AV
COPAREAT3.EO.ST.SV
        COPAREAT3.PU.DT.AV COPAREAT3.PU.DT.SV COPAREAT3.PU.ST.AV
COPAREAT3.PU.ST.SV
        /WSFACTOR=Time 3 Simple(1) Vision 3 Simple(1) Task 2 Polynomial Vibration 2 Polynomial
         /MEASURE=COPAREA
         /METHOD=SSTYPE(3)
         /EMMEANS=TABLES(Time*Vision*Task*Vibration)
         /PRINT=DESCRIPTIVE HOMOGENEITY
         /CRITERIA=ALPHA(.05)
         /WSDESIGN=Time Vision Task Vibration Time*Vision Time*Task Vision*Task
Time*Vision*Task
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```
        Time*Vibration     Vision*Vibration     Time*Vision*Vibration     Task*Vibration
Time*Task*Vibration
        Vision*Task*Vibration Time*Vision*Task*Vibration.

      GLM  COMAPRMST1.EC.DT.AV  COMAPRMST1.EC.DT.SV  COMAPRMST1.EC.ST.AV
COMAPRMST1.EC.ST.SV
      COMAPRMST1.EO.DT.AV     COMAPRMST1.EO.DT.SV     COMAPRMST1.EO.ST.AV
COMAPRMST1.EO.ST.SV
      COMAPRMST1.PU.DT.AV     COMAPRMST1.PU.DT.SV     COMAPRMST1.PU.ST.AV
COMAPRMST1.PU.ST.SV
      COMAPRMST2.EC.DT.AV     COMAPRMST2.EC.DT.SV     COMAPRMST2.EC.ST.AV
COMAPRMST2.EC.ST.SV
      COMAPRMST2.EO.DT.AV     COMAPRMST2.EO.DT.SV     COMAPRMST2.EO.ST.AV
COMAPRMST2.EO.ST.SV
      COMAPRMST2.PU.DT.AV     COMAPRMST2.PU.DT.SV     COMAPRMST2.PU.ST.AV
COMAPRMST2.PU.ST.SV
      COMAPRMST3.EC.DT.AV     COMAPRMST3.EC.DT.SV     COMAPRMST3.EC.ST.AV
COMAPRMST3.EC.ST.SV
      COMAPRMST3.EO.DT.AV     COMAPRMST3.EO.DT.SV     COMAPRMST3.EO.ST.AV
COMAPRMST3.EO.ST.SV
      COMAPRMST3.PU.DT.AV     COMAPRMST3.PU.DT.SV     COMAPRMST3.PU.ST.AV
COMAPRMST3.PU.ST.SV
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       /MEASURE=COMAPRMS
       /METHOD=SSTYPE(3)
       /EMMEANS=TABLES(Time*Vision*Task*Vibration)
       /PRINT=DESCRIPTIVE HOMOGENEITY
       /CRITERIA=ALPHA(.05)
       /WSDESIGN=Time   Vision   Task   Vibration   Time*Vision   Time*Task   Vision*Task
Time*Vision*Task
        Time*Vibration     Vision*Vibration     Time*Vision*Vibration     Task*Vibration
Time*Task*Vibration
        Vision*Task*Vibration Time*Vision*Task*Vibration.

      GLM  COMMLRMST1.EC.DT.AV  COMMLRMST1.EC.DT.SV  COMMLRMST1.EC.ST.AV
COMMLRMST1.EC.ST.SV
      COMMLRMST1.EO.DT.AV     COMMLRMST1.EO.DT.SV     COMMLRMST1.EO.ST.AV
COMMLRMST1.EO.ST.SV
      COMMLRMST1.PU.DT.AV     COMMLRMST1.PU.DT.SV     COMMLRMST1.PU.ST.AV
COMMLRMST1.PU.ST.SV
      COMMLRMST2.EC.DT.AV     COMMLRMST2.EC.DT.SV     COMMLRMST2.EC.ST.AV
COMMLRMST2.EC.ST.SV
      COMMLRMST2.EO.DT.AV     COMMLRMST2.EO.DT.SV     COMMLRMST2.EO.ST.AV
COMMLRMST2.EO.ST.SV
      COMMLRMST2.PU.DT.AV     COMMLRMST2.PU.DT.SV     COMMLRMST2.PU.ST.AV
COMMLRMST2.PU.ST.SV
      COMMLRMST3.EC.DT.AV     COMMLRMST3.EC.DT.SV     COMMLRMST3.EC.ST.AV
COMMLRMST3.EC.ST.SV
      COMMLRMST3.EO.DT.AV     COMMLRMST3.EO.DT.SV     COMMLRMST3.EO.ST.AV
COMMLRMST3.EO.ST.SV
      COMMLRMST3.PU.DT.AV     COMMLRMST3.PU.DT.SV     COMMLRMST3.PU.ST.AV
COMMLRMST3.PU.ST.SV
      /WSFACTOR=Time 3 Simple(1) Vision 3 Simple(1) Task 2 Simple Vibration 2 Simple
       /MEASURE=COMMLRMS
       /METHOD=SSTYPE(3)
       /EMMEANS=TABLES(Time*Vision*Task*Vibration)
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          /PRINT=DESCRIPTIVE HOMOGENEITY
          /CRITERIA=ALPHA(.05)
          /WSDESIGN=Time Vision Task Vibration Time*Vision Time*Task Vision*Task
Time*Vision*Task
           Time*Vibration Vision*Vibration Time*Vision*Vibration Task*Vibration
Time*Task*Vibration
           Vision*Task*Vibration Time*Vision*Task*Vibration.

        GLM COMAPAPENT1.EC.DT.AV COMAPAPENT1.EC.DT.SV COMAPAPENT1.EC.ST.AV
COMAPAPENT1.EC.ST.SV
        COMAPAPENT1.EO.DT.AV COMAPAPENT1.EO.DT.SV COMAPAPENT1.EO.ST.AV
COMAPAPENT1.EO.ST.SV
        COMAPAPENT1.PU.DT.AV COMAPAPENT1.PU.DT.SV COMAPAPENT1.PU.ST.AV
COMAPAPENT1.PU.ST.SV
        COMAPAPENT2.EC.DT.AV COMAPAPENT2.EC.DT.SV COMAPAPENT2.EC.ST.AV
COMAPAPENT2.EC.ST.SV
        COMAPAPENT2.EO.DT.AV COMAPAPENT2.EO.DT.SV COMAPAPENT2.EO.ST.AV
COMAPAPENT2.EO.ST.SV
        COMAPAPENT2.PU.DT.AV COMAPAPENT2.PU.DT.SV COMAPAPENT2.PU.ST.AV
COMAPAPENT2.PU.ST.SV
        COMAPAPENT3.EC.DT.AV COMAPAPENT3.EC.DT.SV COMAPAPENT3.EC.ST.AV
COMAPAPENT3.EC.ST.SV
        COMAPAPENT3.EO.DT.AV COMAPAPENT3.EO.DT.SV COMAPAPENT3.EO.ST.AV
COMAPAPENT3.EO.ST.SV
        COMAPAPENT3.PU.DT.AV COMAPAPENT3.PU.DT.SV COMAPAPENT3.PU.ST.AV
COMAPAPENT3.PU.ST.SV
        /WSFACTOR=Time 3 Simple(1) Vision 3 Simple(1) Task 2 Simple Vibration 2 Simple
          /MEASURE=COMAPAPEN
          /METHOD=SSTYPE(3)
          /EMMEANS=TABLES(Time*Vision*Task*Vibration)
          /PRINT=DESCRIPTIVE HOMOGENEITY
          /CRITERIA=ALPHA(.05)
          /WSDESIGN=Time Vision Task Vibration Time*Vision Time*Task Vision*Task
Time*Vision*Task
           Time*Vibration Vision*Vibration Time*Vision*Vibration Task*Vibration
Time*Task*Vibration
           Vision*Task*Vibration Time*Vision*Task*Vibration.

        GLM COMMLAPENT1.EC.DT.AV COMMLAPENT1.EC.DT.SV COMMLAPENT1.EC.ST.AV
COMMLAPENT1.EC.ST.SV
        COMMLAPENT1.EO.DT.AV COMMLAPENT1.EO.DT.SV COMMLAPENT1.EO.ST.AV
COMMLAPENT1.EO.ST.SV
        COMMLAPENT1.PU.DT.AV COMMLAPENT1.PU.DT.SV COMMLAPENT1.PU.ST.AV
COMMLAPENT1.PU.ST.SV
        COMMLAPENT2.EC.DT.AV COMMLAPENT2.EC.DT.SV COMMLAPENT2.EC.ST.AV
COMMLAPENT2.EC.ST.SV
        COMMLAPENT2.EO.DT.AV COMMLAPENT2.EO.DT.SV COMMLAPENT2.EO.ST.AV
COMMLAPENT2.EO.ST.SV
        COMMLAPENT2.PU.DT.AV COMMLAPENT2.PU.DT.SV COMMLAPENT2.PU.ST.AV
COMMLAPENT2.PU.ST.SV
        COMMLAPENT3.EC.DT.AV COMMLAPENT3.EC.DT.SV COMMLAPENT3.EC.ST.AV
COMMLAPENT3.EC.ST.SV
        COMMLAPENT3.EO.DT.AV COMMLAPENT3.EO.DT.SV COMMLAPENT3.EO.ST.AV
COMMLAPENT3.EO.ST.SV
        COMMLAPENT3.PU.DT.AV COMMLAPENT3.PU.DT.SV COMMLAPENT3.PU.ST.AV
COMMLAPENT3.PU.ST.SV
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          /WSFACTOR=Time 3 Simple(1) Vision 3 Simple(1) Task 2 Simple Vibration 2 Simple
           /MEASURE=COMMLAPEN
           /METHOD=SSTYPE(3)
           /EMMEANS=TABLES(Time*Vision*Task*Vibration)
           /PRINT=DESCRIPTIVE HOMOGENEITY
           /CRITERIA=ALPHA(.05)
           /WSDESIGN=Time Vision Task Vibration Time*Vision Time*Task Vision*Task
Time*Vision*Task
             Time*Vibration Vision*Vibration Time*Vision*Vibration Task*Vibration
Time*Task*Vibration
             Vision*Task*Vibration Time*Vision*Task*Vibration.

          GLM COMAREAT1.EC.DT.AV COMAREAT1.EC.DT.SV COMAREAT1.EC.ST.AV
COMAREAT1.EC.ST.SV
          COMAREAT1.EO.DT.AV COMAREAT1.EO.DT.SV COMAREAT1.EO.ST.AV
COMAREAT1.EO.ST.SV
          COMAREAT1.PU.DT.AV COMAREAT1.PU.DT.SV COMAREAT1.PU.ST.AV
COMAREAT1.PU.ST.SV
          COMAREAT2.EC.DT.AV COMAREAT2.EC.DT.SV COMAREAT2.EC.ST.AV
COMAREAT2.EC.ST.SV
          COMAREAT2.EO.DT.AV COMAREAT2.EO.DT.SV COMAREAT2.EO.ST.AV
COMAREAT2.EO.ST.SV
          COMAREAT2.PU.DT.AV COMAREAT2.PU.DT.SV COMAREAT2.PU.ST.AV
COMAREAT2.PU.ST.SV
          COMAREAT3.EC.DT.AV COMAREAT3.EC.DT.SV COMAREAT3.EC.ST.AV
COMAREAT3.EC.ST.SV
          COMAREAT3.EO.DT.AV COMAREAT3.EO.DT.SV COMAREAT3.EO.ST.AV
COMAREAT3.EO.ST.SV
          COMAREAT3.PU.DT.AV COMAREAT3.PU.DT.SV COMAREAT3.PU.ST.AV
COMAREAT3.PU.ST.SV
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           /MEASURE=COMAREA
           /METHOD=SSTYPE(3)
           /EMMEANS=TABLES(Time*Vision*Task*Vibration)
           /PRINT=DESCRIPTIVE HOMOGENEITY
           /CRITERIA=ALPHA(.05)
           /WSDESIGN=Time Vision Task Vibration Time*Vision Time*Task Vision*Task
Time*Vision*Task
             Time*Vibration Vision*Vibration Time*Vision*Vibration Task*Vibration
Time*Task*Vibration
             Vision*Task*Vibration Time*Vision*Task*Vibration.

          GLM COMAPAP10T1.EC.DT.AV COMAPAP10T1.EC.DT.SV COMAPAP10T1.EC.ST.AV
COMAPAP10T1.EC.ST.SV
          COMAPAP10T1.EO.DT.AV COMAPAP10T1.EO.DT.SV COMAPAP10T1.EO.ST.AV
COMAPAP10T1.EO.ST.SV
          COMAPAP10T1.PU.DT.AV COMAPAP10T1.PU.DT.SV COMAPAP10T1.PU.ST.AV
COMAPAP10T1.PU.ST.SV
          COMAPAP10T2.EC.DT.AV COMAPAP10T2.EC.DT.SV COMAPAP10T2.EC.ST.AV
COMAPAP10T2.EC.ST.SV
          COMAPAP10T2.EO.DT.AV COMAPAP10T2.EO.DT.SV COMAPAP10T2.EO.ST.AV
COMAPAP10T2.EO.ST.SV
          COMAPAP10T2.PU.DT.AV COMAPAP10T2.PU.DT.SV COMAPAP10T2.PU.ST.AV
COMAPAP10T2.PU.ST.SV
          COMAPAP10T3.EC.DT.AV COMAPAP10T3.EC.DT.SV COMAPAP10T3.EC.ST.AV
COMAPAP10T3.EC.ST.SV
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        COMAPAP10T3.EO.DT.AV        COMAPAP10T3.EO.DT.SV        COMAPAP10T3.EO.ST.AV
COMAPAP10T3.EO.ST.SV
        COMAPAP10T3.PU.DT.AV        COMAPAP10T3.PU.DT.SV        COMAPAP10T3.PU.ST.AV
COMAPAP10T3.PU.ST.SV
        /WSFACTOR=Time 3 Simple(1) Vision 3 Simple(1) Task 2 Simple Vibration 2 Simple
         /MEASURE=COMAPAPEN10
         /METHOD=SSTYPE(3)
         /EMMEANS=TABLES(Time*Vision*Task*Vibration)
         /PRINT=DESCRIPTIVE HOMOGENEITY
         /CRITERIA=ALPHA(.05)
         /WSDESIGN=Time    Vision    Task    Vibration    Time*Vision    Time*Task    Vision*Task
Time*Vision*Task
          Time*Vibration        Vision*Vibration        Time*Vision*Vibration        Task*Vibration
Time*Task*Vibration
          Vision*Task*Vibration Time*Vision*Task*Vibration.

        GLM  COMMLAP10T1.EC.DT.AV  COMMLAP10T1.EC.DT.SV  COMMLAP10T1.EC.ST.AV
COMMLAP10T1.EC.ST.SV
        COMMLAP10T1.EO.DT.AV      COMMLAP10T1.EO.DT.SV      COMMLAP10T1.EO.ST.AV
COMMLAP10T1.EO.ST.SV
        COMMLAP10T1.PU.DT.AV      COMMLAP10T1.PU.DT.SV      COMMLAP10T1.PU.ST.AV
COMMLAP10T1.PU.ST.SV
        COMMLAP10T2.EC.DT.AV      COMMLAP10T2.EC.DT.SV      COMMLAP10T2.EC.ST.AV
COMMLAP10T2.EC.ST.SV
        COMMLAP10T2.EO.DT.AV      COMMLAP10T2.EO.DT.SV      COMMLAP10T2.EO.ST.AV
COMMLAP10T2.EO.ST.SV
        COMMLAP10T2.PU.DT.AV      COMMLAP10T2.PU.DT.SV      COMMLAP10T2.PU.ST.AV
COMMLAP10T2.PU.ST.SV
        COMMLAP10T3.EC.DT.AV      COMMLAP10T3.EC.DT.SV      COMMLAP10T3.EC.ST.AV
COMMLAP10T3.EC.ST.SV
        COMMLAP10T3.EO.DT.AV      COMMLAP10T3.EO.DT.SV      COMMLAP10T3.EO.ST.AV
COMMLAP10T3.EO.ST.SV
        COMMLAP10T3.PU.DT.AV      COMMLAP10T3.PU.DT.SV      COMMLAP10T3.PU.ST.AV
COMMLAP10T3.PU.ST.SV
        /WSFACTOR=Time 3 Simple(1) Vision 3 Simple(1) Task 2 Simple Vibration 2 Simple
         /MEASURE=COMMLAPEN10
         /METHOD=SSTYPE(3)
         /EMMEANS=TABLES(Time*Vision*Task*Vibration)
         /PRINT=DESCRIPTIVE HOMOGENEITY
         /CRITERIA=ALPHA(.05)
         /WSDESIGN=Time    Vision    Task    Vibration    Time*Vision    Time*Task    Vision*Task
Time*Vision*Task
          Time*Vibration        Vision*Vibration        Time*Vision*Vibration        Task*Vibration
Time*Task*Vibration
          Vision*Task*Vibration Time*Vision*Task*Vibration.
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