2011

Neural Responses to Vibration during Wobble Board Balancing

Michael Nguyentat
Claremont McKenna College

Neural Responses to Vibration during Wobble Board Balancing

A Thesis Presented

By

Michael T. Nguyentat

To the Joint Science Department
Of The Claremont Colleges
In partial fulfillment of
The degree of Bachelor of Arts

Senior Thesis in Neuroscience

April 25, 2011

TABLE OF CONTENTS

ABSTRACT

Falling, an epidemic most prevalently seen in the elderly population, accounts for the majority of injury-related cases seen by emergency departments across the United States. Unfortunately, with no large-scale institutionalization of a solution, the problem is only expected to exacerbate as our planet's population approaches the 7 billion mark. In the wake of the recent surge of falls among the elderly, Japan has implemented a program to include unicycling in the physical education curriculum for elementary schools across the country. The goal for this program is to encourage children to establish strong fundamental balancing skills, which could potentially alleviate the pain—physical, emotional, and financial—incurred from falls in the elderly. This senior thesis study builds off Japan's unicycling program by investigating ways to improve wobble board balancing, a more practical alternative to unicycling. In previous research, the skill of stick balancing, a motor task that has been shown to behave with the same power laws as wobble board balancing, has been improved with the use of vibrations. Here, we show that learning to wobble board balance is not expedited and wobble board balancing skill is not improved with the employment of vibrations, unlike stick balancing. Nonetheless, those who learned to wobble board balance with background vibrations went on to later outperform those who learned to wobble board balance without vibrations. These results suggest that vibrations (50 Hz, 0.18 mm amplitude) have a beneficial effect on the development of skill for wobble board balancing that is not related to the direct physical effects of the vibration. The observations also suggest that in the presence of vibrations, the nervous system develops more robust strategies for controlling balance.

INTRODUCTION:

Falling has become a medical nightmare for those in the elderly community, and the problem is only expected to exacerbate as the elderly population expands to include the "baby boomer" generation. Thus, it remains imperative that researchers continue seeking ways to either slow the degradation process, equip people with better balancing skills, or develop technology to help slow the normal degenerative effects of aging. Failure to do so will result in large costs—physically, emotionally, and financially—to our society. Already, falling accounts for the majority of injury-related cases seen by emergency departments across the United States and is the leading cause of accidental death for those over the age of 65 (Fuller, 2000). For accidental deaths over 75 years of age, 70% are attributed to falls. In total, the financial cost for falls in those over 65 years of age exceeded $19 billion in 2000 (Stevens, *et. al.*, 2006). Even worse, the costs and number of deaths stemming from falls in the elderly are expected to grow (Fuller, 2000; Englander *et. al.*, 1996; Tideiksaar, 1988). Those who manage to survive their falls often experience a debilitating decline in activities of daily living (ADL) as they become isolated, immobile, or depressed due to their fear of falling again (Fuller, 2000). Thus, not only do the elderly decline physically and functionally, but they also suffer from psychological decline after falling. Unfortunately, all these numbers are only underestimates of the actual number of falls and costs. The majority of falls within the elderly population go unreported because of the embarrassment one suffers, or because of the fear of loved ones placing the elderly in a nursing home or some other type of institution after a traumatic fall (Tideiksaar, 1988). Consequently, the need for a resolution is even greater than the numbers suggest.

To help treat and prevent future falls, one must understand the causes of falls. The most common explanation for falling among the elderly is the degenerative effect of aging (Wolfson *et. al.*, 1985). As the function of the human musculoskeletal system deteriorates, our balance, gait, and reaction times—all of which are important for avoiding or correcting a fall (Tideiksaar, 1988)—soon follow suit. This total body degradation is regrettably, a natural cycle of life and current technology has not offered any procedures to nullify or prevent the inevitable. Nonetheless, due to the increase in concern for the health risks and the implications resulting from falls in the elderly, a vast amount of research has gone into preventing falls. For example, one research endeavor has generated assessment techniques and rubrics, called “Balance Scale scores” to predict the likelihood of an elderly person falling (Berg *et. al.*, 1992). However, much of the existing literature focuses on fall prevention only after the elderly have reached old age. Little information has emerged about preventing falls before the onset of old age. Potentially, prevention serves as an important avenue for future research.

One innovative approach in preventing falls prior to old age was implemented in Japan in 1989. Japan’s Ministry of Education added unicycling as part of the physical education curriculum for elementary school children. Now, most schools in Japan have unicycles (www.web-japan.org). A goal for the institutionalization of unicycles was to improve balance in children. An unappreciated skill among young children, the mastery of balancing could potentially be conserved throughout one’s youth, into adulthood, and even reach into old age. As a result, improved balance could yield large dividends as the young population of Japan ages.

Since the program is still in its infancy, very little research, especially in the western world, has gone into investigating how to improve the balance of children learning to ride unicycles. However, improving the process of learning to unicycle and making it more efficient could increase the benefits of Japan's program and provide useful balancing information for people all around the world. Moreover, previous studies have shown that a motor skill such as stick balancing could be enhanced by simultaneously employing whole-body vibrations (Milton *et. al.*, 2009b). The goal of this thesis was to determine how vibrations affect the speed at which subjects acquire a proficient skill in the unicycling equivalent, wobble board balancing. As a second goal, we wanted to understand how the employment of novel vibrations would affect the performance of intermediate-level wobble board balancers.

BACKGROUND:

Bipedalism

For years, humans have been awed by the balancing skills of their primate relatives and other animals, envying their ability to climb the thin and swaying branches of a crowded canopy. Tourists gather at the Earth's natural forests all over the world to revel in the animals' mastery of combining agility and balance in their reign over the jungle tree tops throughout the globe. Attempts at mimicking the supreme balancing skills of their ancestors have not even come close to achieving the same adroitness, even by their species' most advanced balancers (i.e. dancers, surfers, trapeze artists, and gymnasts). So, why are there deficits in human balancing, when their ancestors exhibited highly refined balance abilities?

Somewhere along the line of evolution, humans diverged towards a less stable form of locomotion—bipedalism. Bipedalism is the phenomenon in which humans stand on two limbs, in contrast to the four limbs most animals employ. Standing erect on two feet raises the height of human's center of mass (COM), since their legs make up a large proportion of their total height. This shift in COM, without a corresponding expansion in the support base, makes humans more prone to being affected by changes in equilibrium than their four-legged counterparts. Additionally, it makes falls more injurious, because the fall occurs at a greater distance from the ground (Skoyles *et. al.*, 2006; Casadio *et. al*, 2005). Thus, their newly developed form of balance remains innately unstable and makes humans increasingly vulnerable to injury.

Human Balancing Mechanisms and Strategies

To understand how humans compensate for their inherently defective balancing stance, substantial research has gone into understanding how the nervous system works to maintain balance. A wealth of information has consequently emerged about the central nervous system (CNS) and how it allows humans to maintain a stable COM during locomotion or other types of movement. The CNS's constant readjustment commands enable humans to remain upright and establish a dynamic equilibrium on two feet. But how exactly does the CNS do this?

To answer this question, researchers have approached the problem from mathematical and physical, anatomical, and theoretical standpoints. In terms of a mathematical and physical avenue, investigators have studied balancing through the behavior of another intrinsically unstable example: the inverted pendulum (Kuo, 1993). Like bipedalism, the

COM for an inverted pendulum is focused above its narrow base, allowing minute external forces to cause the pendulum to deviate from its perpendicular axis and fall. While there are obvious differences between inverted pendulums and human balancing, researchers (Gage *et. al*, 2003) have undertaken experiments to validate the model as a sufficient alternative for studying human balancing with humans themselves. Hence, using this model allows researchers to investigate the natural falling movements and tendencies of an object with a high COM, without any interference from the CNS.

Aside from mathematical models of falling inverted pendulums, theories for balance control—such as the passive control theory, the active control theory, and the drift and act theory—have surfaced. The passive control theory and active control theory differ upon one main principle: neural feedback control. The passive control theory suggests that bipedal balancing is sustained irrespective to CNS feedback. This theory hypothesizes that the human body is equipped with natural elastic and stiffness properties within its joints, ligaments, tendons, and muscles, which are sufficient for maintaining equilibrium (Winter *et. al.*, 1998). In contrast, the active control theory offers a hypothesis of continuous feedback. Here, neural responses are constantly being elicited by changes in equilibrium; thus, neural commands are continuously being employed to sustain a stable upright stance. Although both of these theories greatly conflict with each other, they are similar in their faltering point. Basing balance completely on neural feedback or completely on non-neural attributes seems too extreme.

Although research has acknowledged that the intrinsic muscle and joint stiffness provide substantial balance support, these properties are not sufficient enough to independently maintain balance (Loram, *et. al.*, 2002). Instead, there seems to be some interplay between the feedback and non-feedback pathways. Further, Loram, *et. al.*, 2002 showed that intermittent and ballistic muscle movements are needed to control balance. These sporadic movements come as a response to the difficulty of attaining perfect equilibrium. Therefore, increases and decreases in whole-body torque during a “throw and catch pattern” and a “drop and catch pattern”, respectively, become necessary (Loram, *et. al.*, 2002). Similar to the inverted pendulum model of the human balancing, stick balancing, a task in which a person balances a wooden dowel on the tip of their finger, displays the same type positive feedback with discontinuous, ballistic control impulses (Cabrera *et. al.*, 2002; Cabrera *et. al.*, 2004).

The fact that positive feedback and discontinuous control exist for balancing (Milton *et. al.*, 2009a) makes room for the “Drift and Act” control mechanism to emerge. This theory serves as a hybrid model of the passive and active control theories and conforms to the intermittent and ballistic principles of positive feedback. As an object with inverted pendulum dynamics sways from a perpendicular position, it is allowed to “drift” within a small basin of attraction. In this instance, no neural feedback is utilized. Only when the deviations from the perfect upright position breach the boundaries of this basin does feedback present its influence (Milton *et. al.*, 2009b). On the edge of destabilization, the CNS will call upon corrective actions for restabilization within the basin of attraction. Thus, the “Drift and Act” control model provides a moderate alternative to the two extremes proposed by the passive and active control theories.

Anatomically, there are three main sensory systems that contribute to the CNS’s control of balance: the visual system, proprioceptive system, and the vestibular system (Redfern *et. al.*, 2001). Eyes provide vital visual input from the environment to detect any changes in equilibrium that would necessitate the human body to make adjustments for restabilization. The proprioceptive system provides a sense of where one's body parts are in relation to each other and space. To do this, the proprioceptive system utilizes prioprioceptors, such as stretch receptors and muscle spindles, to detect stimuli and relay the information through Type I and Type II afferent nerves (Purves *et. al.*, 2008). More specifically, somatosensory cues in the feet and ankles provide valuable information that is used to minimize postural sway (Mauer *et. al.*, 2001). In the vestibular system, two different sensors are exploited to aid balance: otoliths and semicircular canals, which detect linear acceleration and angular acceleration in three planes, respectively (Ivanenko *et. al.*, 1997). The hair cells associated with these sensors send information via afferent nerves to be evaluated in the brain.

Once information has been collected in the brain, the cerebellum presides over the integration of input from all three systems. Sometimes, one of the systems falters, or multiple systems give conflicting or undecipherable information (i.e. retina stimulation can give ambiguous information about self-motion and external motion). In this case, the cerebellum is able to "weight" the incoming information to rely more heavily on the system that provides the most precise information (Morton *et. al.*, 2004). Determining the exact mechanisms or balance pathways in the cerebellum is difficult because cerebral damage or disease is usually not localized to the cerebellum. Nonetheless, although specifics by which the cerebellum controls balance may be unknown, research has shown that the cerebellum remains essential for maintaining equilibrium (Morton *et. al.*, 2004). A damaged or diseased cerebellum results in the disruption of normal sitting, standing, and gaiting, which makes one more susceptible to falling.

How Vibrations Affect the Musculoskeletal System

The scope of this thesis is concentrated on the effects of vibration during balancing. Vibrations were the main focus of this thesis because of the depth to which vibrations have been explored in balancing during locomotion, sitting, and quiet standing. Every day, humans and their bodies are subjected to various forms of vibration, whether it be from sitting in an automobile, walking on the street, going to concerts, or talking on the phone—vibrations are all around. However, even with all the available information about vibrations, their influences on the human body are still vague. Due to the large variability in how vibrations are transferred through the body (Matsumoto *et. al.*, 1998) and how the body responds (Griffin, 1981), it is difficult to outline a steadfast rule which can determine how vibrations will affect a specific individual. In fact, certain vibrations may produce deleterious effects like spinal degeneration, while others yield advantageous effects such as increases in growth hormone and testosterone (Matsumoto *et. al.*, 1998; Cardinale *et. al.*, 2003). Further complicating our understandings of how vibrations are transferred through the human body are the nonlinearities in our musculoskeletal system (Kiiski *et. al.*, 2008). Thus, because of the nebulous influence that vibrations have on the human body, it is appropriate to pursue whole-body vibrational investigations even further.

In muscles, vibrations have been shown to attenuate with distance (Garg *et. al.*, 1976). Travelling through the musculoskeletal system, vibrations can resonate, creating oscillations at greater amplitudes with some frequencies more than others, at different parts of the body (Benzi *et. al.*, 1981). As the vibrations reach the muscles, they exert their influence on the performance of motor skills by acting on the skeletal muscles and their spindles (Proske *et. al.*, 1993; Sorensen *et. al.*, 2002). The vibration stimulus excites Ia afferent nerves, causing α-motor neurons to fire electrical signals to motor units, which consequently contract and yield the tonic contraction of muscles (Jordan *et. al.*, 2005). Single bouts of this type of stimulus have been shown to improve jumping abilities, strength, and body balance (Torvinen *et. al.*, 2002).

Corresponding with this information is the data from a previous Joint Science Department thesis by Janelle Gyorffy. In her thesis, Gyorffy applied vibrations with a 0.18 millimeters amplitude to subjects' Achilles tendons during bilateral stances. She found that vibrations increased stabilization while causing the center of pressure (COP) to fluctuate faster and deviate within a smaller area. Thus, although many studies have shown that whole body vibrations impair one's proprioception and balance (Jordan *et. al.*, 2005; Ivanenko *et. al.*, 2000), balance can also paradoxically be improved with the application of vibrations (Gyorffy, 2009; Torvinen *et. al.*, 2002).

Stick Balancing and Wobble Board Balancing

Applying vibrations to another motor task, stick balancing, yielded a similar improvement. When a subject stood on a vibrating platform (0.001 m amplitude running at 50 Hz) and performed the stick balancing task, the subject exhibited longer mean stick balancing times than when performing the same task without vibrations (Milton *et. al.*, 2009b). It was determined that during this exercise, the movement of the sticks took on a characteristic Lévy distribution curve. Moreover, in another previous Joint Science Department student thesis, Larry Wang showed that stick balancing and wobble board balancing shared equivalent power laws and Lévy distribution curves. Thus, the two activities mirror each other in terms of balancing tasks and skills since they share equivalent dynamics and fluctuations.

Due to the similarity between stick balancing and wobble board balancing, it was questioned whether the same results from stick balancing could be obtained with wobble board balancing. Although the main goal of this thesis was to decode the effects of vibrations while unicycling, a unicycle was substituted for a wobble board because of their own similarities and general practicalities. Matsumoto *et. al.* (1998) showed that vibrations cause resonant frequencies in the normal standing posture—as seen in stick balancing—that are similar to those in the seated posture. Therefore, using a wobble board as an alternative to a unicycle was a suitable substitution.

METHODS:

Setting

This study was approved by the institutional review board at Claremont McKenna College in accordance with the currently applicable U.S. Public Health Service Guidelines. All participants provided written informed consent for all research testing. In investigating the effects of vibration on wobble board balancing, two experiments were conducted to determine the affect of vibrations on balance during learning and training for novice-level subjects, and how vibrations affect an intermediate-level balancer. These experiments were conducted over a period of 12 days, from February 28, 2011 through March 11, 2011, in Professor John Milton's office in the Keck Science Center of the Joint Science Department of the Claremont Colleges. Limited by the time constraints for completing the study, participants were scheduled to come in for the experiment between the hours of 8:00 AM and 11:30 PM.

Calibration

Prior to the start of the experiments we calibrated the vibrational amplitude output of a Globus Physioplate Gold exercise machine (using high-speed Qualysis Oqus 300 cameras and Qualysis passive reflective markers). Because the amplitudes measured directly on top of the platform were too extreme, the floor of the laboratory was used as a vibration filter. Amplitudes generated from frequencies between 10-20 Hz were not calibrated because vibrations at these levels can produce deleterious effects on human body segments, like the spine, due to its proximity to the human body's natural resonance frequency (Kiiski *et. al.*, 2008; Matsumoto *et. al.*, 1998; Rassmussen, 1983; Garg *et. al.*, 1976). After measuring the amplitudes at various distances from the platform, an initial vibrational output map was concocted (Table 1) for the Globus Physioplate Gold running at 50 Hz, and 70 Hz. However, in order to determine if the principle of "motor skill improvement with vibrations" could be applied to wobble board balancing (and eventually unicycle riding), attempts were made to reproduce the vibration conditions used to improve stick balancing (Milton *et. al.*, 2009b). Therefore, the frequency output was set at 50 Hz for the remainder of the experiment. In contrast to the conditions used by Milton *et. al.*, 2009b, the wobble board was placed on the floor, four feet from the platform, instead of directly on top of the platform (Figure 1A & 1D). The main reason for this was because the amplitude of vibration four feet from the platform was closest to the 0.18 mm value at which the bilateral stabilization effects of vibrations peaked for postural sway (Gyorffy, 2009). Another auxiliary reason was to ensure that the participants' visual acuity would not be compromised as a result of the large working frequency experienced directly on top of the platform (Garg *et. al.*, 1976).

Table 1. Summary of vibrational amplitude. The vibrational output of the Globus Physioplate was mapped out and summarized in the table, showing the relationship of the vibrational amplitude with the frequency and distance from the Globus Physioplate.

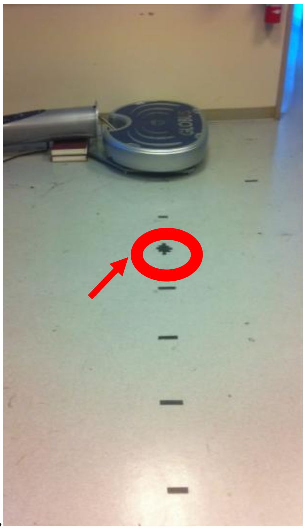
Distance (ft) from Globus Physioplate	Amplitude (mm) at 50 Hz	Amplitude (mm) at 70 Hz
0 (directly on the platform)	2.2	4
3	0.09	0.14
4	0.18	0.13
5	0.13	0.13
6	0.11	0.11
7	0.07	n/a
8	0.08	n/a

Initial screening of subjects

Gathering participants for the experiments was coupled with a screening process. First, a group of 26 students from the Claremont Colleges was invited to fill out a preliminary questionnaire (Appendix I) about their previous balancing experiences as well as any previous injuries that may have an effect on their current balance abilities. Then, the students were asked to participate in an initial 10-trial screening stage. During the 10 trials, participants were asked to wear comfortable shoes, stand on the "Tri-level Design" Fitter First Wobble Board, bend their knees to reduce their body stiffness and absorb any employed vibrations (Lafortune *et. al.*, 1996), and balance for as long as feasible. Meanwhile, their balancing abilities were timed using a hand-help stop watch. Since there was only a small difference in survival function between wobble board balancing in the frontal and sagittal planes (Wang, 2009), only the sagittal plane was used for balancing because it appeared to be safer. Each subject was instructed to use a chair, placed either to their side (Figure 1C) or in front of them (Figure 1B), to stabilize themselves before attempting to balance freely. Once the subject attained equilibrium and released their hand from the supporting chair, timing commenced. Timing promptly ended as soon as one of the edges of the wobble board made contact with the ground, thus, concluding one trial.

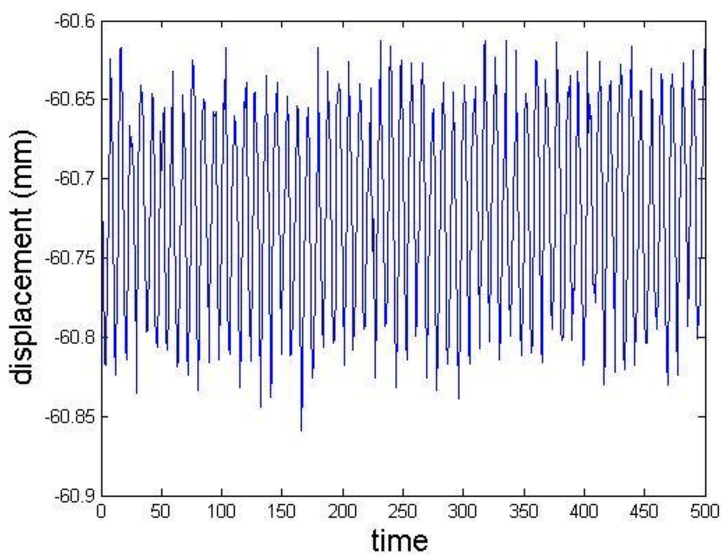
For each of the 26 subjects, ages 18-29, their 10-trial data was entered into the *SurvivalCurve.m* MATLAB program (Appendix II). This program generated a survival curve, which shows the log-log plot of the fraction of those still balancing versus the time, and determined their $T_{1/2}$ value. This $T_{1/2}$ value, which was essentially just the mean balancing time, was the basis of for the decision on whether to retain or dismiss the subject for the experiments. Since the first experiment was focused on determining the effects of vibration during the learning and training of novice balancers, the desired subjects had a $T_{1/2}$ value of less than 10 seconds. So, the initial screening stage allowed for the filtering of intrinsically more advanced subjects with larger $T_{1/2}$ values. On top of that, the questionnaires were used to eliminate those with a compromised balance, due to previous injuries or trauma. Thus, the original group of 26 subjects was decreased down to 21 novice-level subjects.

Figure 1. Initial screening trials. The placement of the wobble board was four feet from the Globus Physioplate (A) where the vibrational amplitude was determined to be closest to 0.18mm (D). The subjects used a chair, either in front of them (B) or to the side of them (C) to begin their trial at equilibrium.

A. 

B. 

C. 



D.

Group Separation and Financial Compensation

The remaining subjects were split into two groups: the Variable Group (VG) and the Control Group (CG), which would learn and practice wobble board balancing with and without vibrations, respectively, during the Vibration Training Experiment (Experiment 1). During the group separation, fatigue was anticipated to play a factor during the experiment. Participating in numerous trials often fatigued many of the researchers' muscles in preliminary test results. Also, previous studies show that although one may not consciously feel fatigued by the vibrations, vibrations induce a decrease in power in EMG for muscles, a telling sign of fatigue (Torvinen *et. al.*, *2002*). Therefore, to control for differences between males' and females' different fatigue rates, fatigue compensation strategies, stiffness coefficients, and muscle co-activation ratios (Padua *et. al.*, 2006), attempts were made to try to allocate an equivalent amount of males and females to each group. To further equate the two groups, attempts were made to ensure the number of total subjects and the initial $T_{1/2}$ average of each group the same (Table 2).

Table 2. Group separation breakdown. The number of male, female, and total subjects, along with the average of each group's initial $T_{1/2}$ is displayed.

	Variable Group	**Control Group**
group average of initial $T_{1/2}$	4.48 (n = 10)	4.76 (n = 11)
number of male	4	4
number of female	6	7

Before the beginning of Experiment 1, the subjects were promised financial compensation for their time, with the amount being determined by their level of involvement throughout the experiments. Also, subjects were to be given a bonus for achieving a $T_{1/2}$ of two minutes; this served as motivation for the subjects to try their best, rather than scheming to involve themselves for the bare minimum requirement to acquire the highest financial compensation possible.

Experiment 1: Vibration Training Experiment

The first experiment, the Vibration Training Experiment, tested how vibrations during skill acquisition for novice-level learners affected the speed at which they learned the wobble board balancing motor skill. All 21 subjects were allowed to practice their wobble board balancing skills for one training period per day; each period was defined as either two minutes of total balancing time on the wobble board (the sum of all the trials) or 20 trials, whichever allowed for the most practice time. Each subject practiced his or her wobble balancing under the same conditions as the initial trials—four feet from the Globus Physioplate, with the help of a chair to achieve initial equilibrium (Figure 1A, 1B, & 1C). However, the Variable Group (VG) practiced as the Globus Physioplate vibrated the floor with an amplitude of ~0.18mm (Figure 1D). Meanwhile, the Control Group (CG) trained devoid of any vibrations.

During each training period, each trial was timed, and the subsequent data was put into the *SurvivalCurve.m* MATLAB program (Appendix II) to determine the subjects' $T_{1/2}$ for that specific training period. We continued each subject's training until each participant's $T_{1/2}$ fell within a range of 15-25 seconds. In this skill level range, the subject was considered to be an intermediate-level wobble board balancer. Thus, the participant was removed from Experiment 1 and placed into the second experiment, the Vibration Effects Experiment. However, if the subject completely surpassed the range defining intermediate skill level, the subject was removed from the Vibration Training Experiment and did not participate in Experiment 2. After the completion of Experiment 1, MATLAB was used run Rank Sum Tests to determine the statistical significance of the data of both groups.

One of the caveats and limitations of Larry Wang's thesis was that participants with less advanced skill levels did not exhibit the same type of power laws in wobble board balancing as stick balancing. Thus, the first experiment was able to serve two purposes. The first was, as aforementioned, to investigate how the vibrations affect the speed at which beginners learn a motor skill. The second purpose was to preface the second experiment. By allowing participants to increase their skill level in Experiment 1, the second experiment was better conducted and allowed for the determination of whether vibrations had the same effect for wobble board balancing as they did for stick balancing.

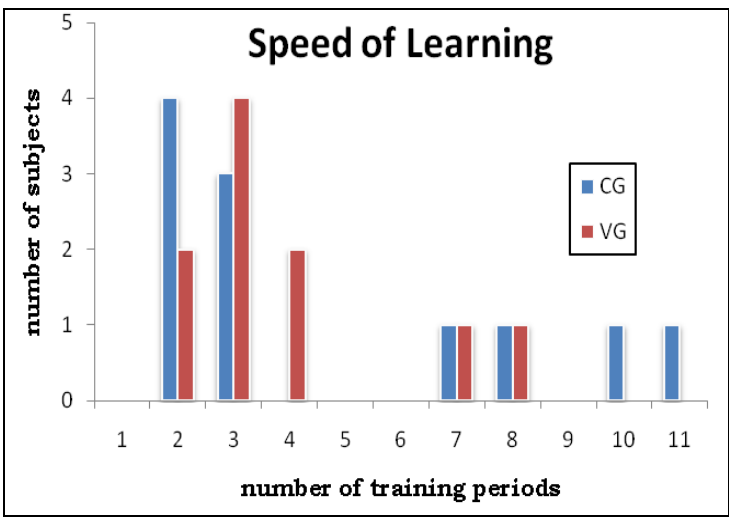
Experiment 2: Vibration Effects Experiment

The second experiment, Vibration Effects Experiment, tested the effect of vibrations on intermediate-level balancers. The remaining participants that had moved on to Experiment 2, from Experiment 1 (Table 3), were asked to participate in 60 trials over the course of three days; all 60 trials were not conducted in one day because of our concern for fatiguing skewing the results. So, each participant, whether they were from the VG or CG of Experiment 1, went through 20 trials per day, with half of the trials conducted with vibrations and the other half conducted without vibrations. In order to prevent the subjects from getting into a rhythm, facilitated by a predictable pattern of vibration and non-vibration trials, the sequence of trials was randomly generated using the *mikevib.m* MATLAB program (Appendix III).

Following each day during the Vibration Effects Experiment, the *SurvivalCurve.m* program (Appendix II) generated a survival curve and determined the subjects' $T_{1/2}$ for his or her set of vibration and non-vibration trials for that particular day. Once the subject completed the third day of Experiment 2, the program was used to determine the three-day combined survival curve. It was also used to compute the $T_{1/2}$ value for each subject's set of 30 trials with and 30 trials without vibrations. Upon the completion of Experiment 2, MATLAB was used to run Rank Sum Tests to determine the significance of the data for both groups.

RESULTS:

Experiment 1: Vibration Training Experiment (VTE)



AVERAGE NUMBER OF TRAINING PERIODS	
Control Group "CG" (n = 11)	**Variable Group "VG" (n = 10)**
4.8	3.9

Figure 2. Speed at which subjects learned to wobble board balance at an intermediate skill level. For each group, the histogram shows the frequency of the number of days needed to achieve an intermediate wobble board balancing skill level. The difference between the groups' speed in achieving the intermediate skill level was not statistically significant ($P = 0.9710$; Rank Sum Test).

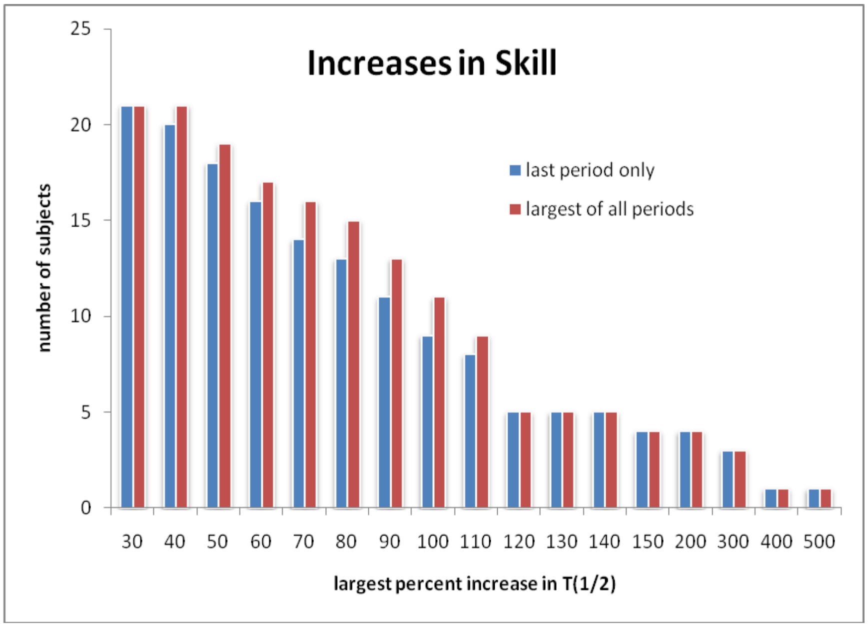


Figure 3. Largest incremental increases in skill for each participant. Comparing the $T_{1/2}$ values of two consecutive training periods allowed for the calculation of the percent increase in skill. The graph gives an overview of the largest increases in skill for each participant, and it shows how many subjects achieved a certain percentage of skill level increase. The blue bars indicate the percent increase in skill during the last two consecutive training days for each participant. The red bars indicate the largest percent increase in skill that occurred during any two consecutive training periods during Experiment 1.

With continued practiced, each subject was able to improve their wobble board balancing skills. Eventually, each participant achieved an intermediate skill level, which was predetermined to be a $T_{1/2}$ value of 15-25 seconds. Figure 2 shows the number of subjects that were able to attain an intermediate skill level in a given amount of training periods. The Variable Group (VG), consisting of 11 subjects, showed a distribution concentrated around the left side of the graph, while the Control Group (CG), consisting of 10 subjects, displayed a distribution that spanned the entire area of the graph. On average, the Variable Group progressed and developed their skill almost one whole training period (0.9 training periods) before the Control Group. However, the difference in speed for acquiring an intermediate skill level was not statistically significant (P = 0.9719; Rank Sum Test).

The acquisition of skill was characterized by steady improvement, and ended with a large incremental increase. During this increase, the $T_{1/2}$ value usually fell within the defined intermediate skill level range. In Figure 3, the largest of the participants' increases are given in terms of percent increase between consecutive $T_{1/2}$ values. Most of the subjects experienced a large "jump" in skill proficiency, as seen by a large percent increase (Figure 3). Upon further examination, it is apparent that 15 of the 21 subjects (70% of the subjects) exhibited at least an 80% increase in skill during consecutive training days at some point during Experiment 1. Of these 15 subjects, the majority of them (13 of 15) experienced their largest increase in skill during their last two days of Experiment 1. Four of these 13 subjects displayed increases that surpassed the defined intermediate skill level, thereby excluding themselves from Experiment 2.

Experiment 2: Vibration Effects Experiment (VEE)

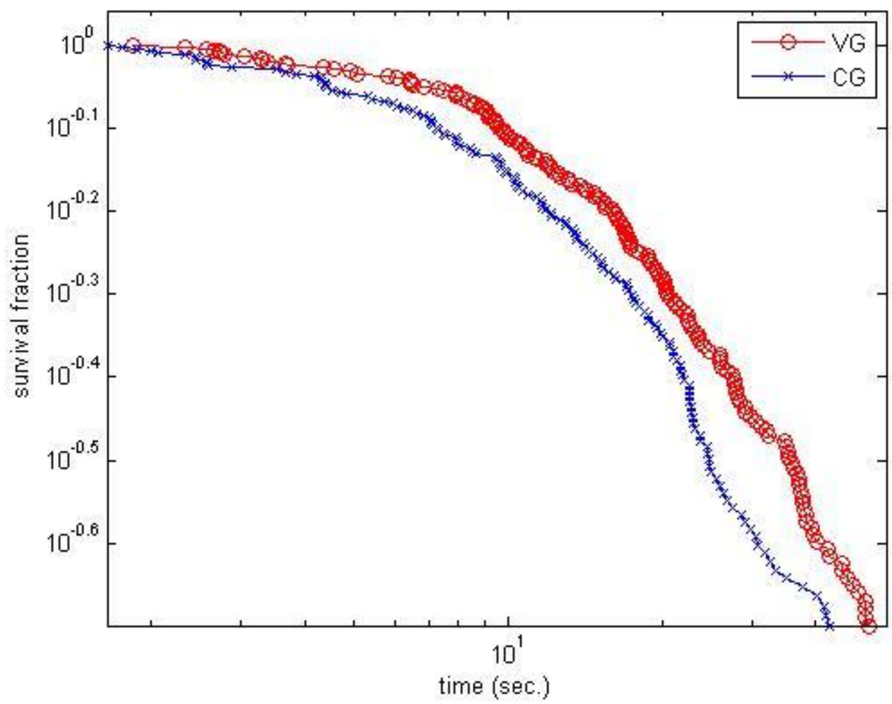
	Variable Group	**Control Group**
Group average of initial $T_{1/2}$	19.5 s (n = 7)	17.5 s (n = 6)
number of males	3	3
number of females	4	3

Table 3. Group breakdown for Experiment 2. The number of original male, female, and total subjects who were kept to participate in Experiment 2 is shown. The new Variable and Control Group $T_{1/2}$ averages are also given for these remaining subjects. The difference in skill level and the difference in number of male and female for each group is statistically insignificant ($P = 0.1807$ and $P = 1.000$, respectively; Rank Sum Test).

Since several subjects surpassed the $T_{1/2}$ range that defined the intermediate skill level for wobble board balancing, only 13 of the original 21 participants were retained from Experiment 1 and asked to participate in Experiment 2 (Table 3). Seven subjects were kept from the Variable Group of Experiment 1, while six subjects were kept from the Control

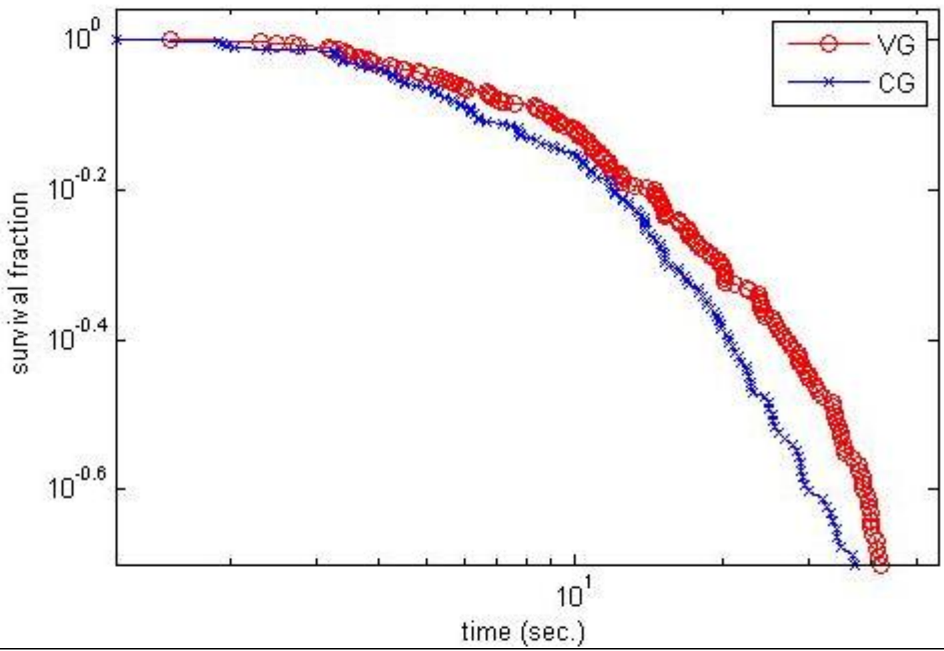
Group of Experiment 1. The differences between the two groups was insignificant in terms of the number of total people, number of males and females (P = 1.000; Rank Sum Test), and skill level—given by the $T_{1/2}$ value (P = 0.1807; Rank Sum Test). Thus, the groups were essentially the same.

Comparisons Between the Groups



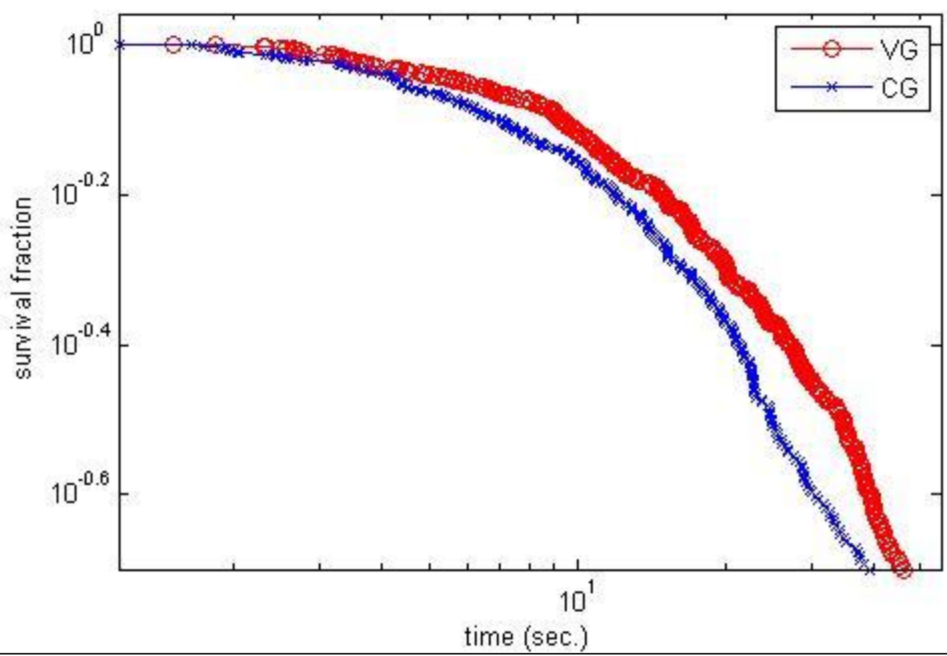
$T_{1/2}$ VALUE FOR TRIALS WITH VIBRATIONS	
Variable Group "VG" (n = 420)	**Control Group "CG" (n = 360)**
33.1 s	25.6 s

Figure 4. Survival curve for vibrations—VG vs. CG. This graph contrasts the Variable Group (VG) and the Control Group (CG) survival curves. The survival curve of the VG is made up from the collection of 420 trials conducted for this group under vibration conditions in Experiment 2. Meanwhile, the survival curve of the CG is a collection of the 360 trials conducted for this group under the same conditions. The fact that the $T_{1/2}$ value for the VG is higher than that of the CG is statistically significant (P = 0.0154; Rank Sum Test).



$T_{1/2}$ VALUES FOR TRIALS WITH NO VIBRATIONS	
Variable Group "VG" (n = 420)	**Control Group "CG" (n = 360)**
28.7 s	24.8 s

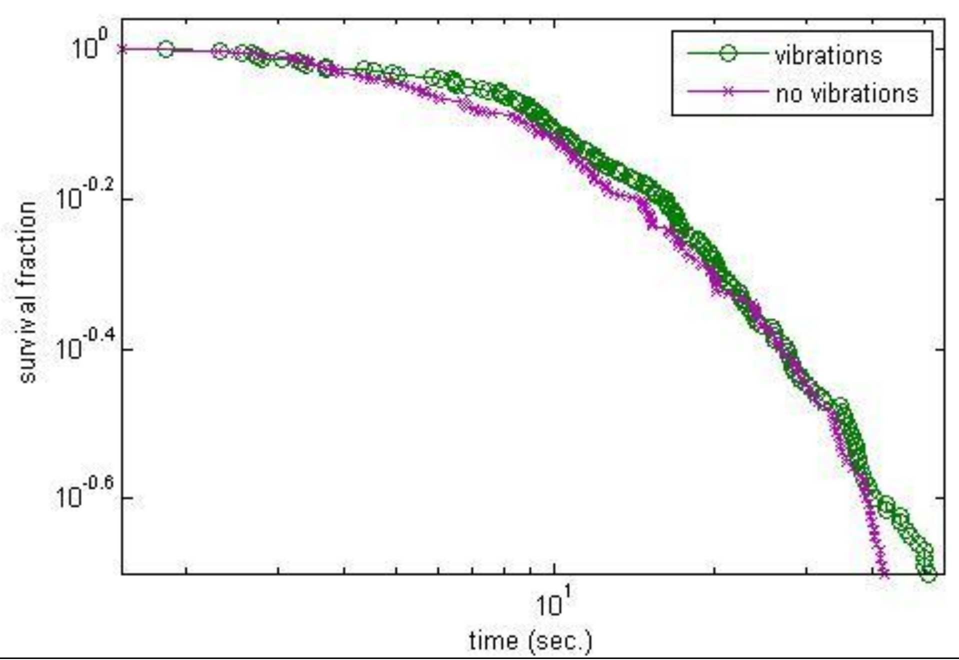
Figure 5. Survival curve for no vibrations—VG vs. CG. This graph depicts the survival curves of the Variable Group (VG) and the Control Group (CG) during trials without vibrations. The survival curve for the VG is made up from the collection of 420 trials conducted for this group under these conditions in Experiment 2. On the other hand, the survival curve for the CG is a collection of the 360 trials conducted under the same conditions. The $T_{1/2}$ value for the VG is significantly higher than that of the CG (P = 0.0500; Rank Sum Test).



OVERALL $T_{1/2}$ VALUES, WITH AND WITHOUT VIBRATIONS	
Variable Group "VG" (n = 840)	**Control Group "CG" (n = 720)**
30.9 s	25.2 s

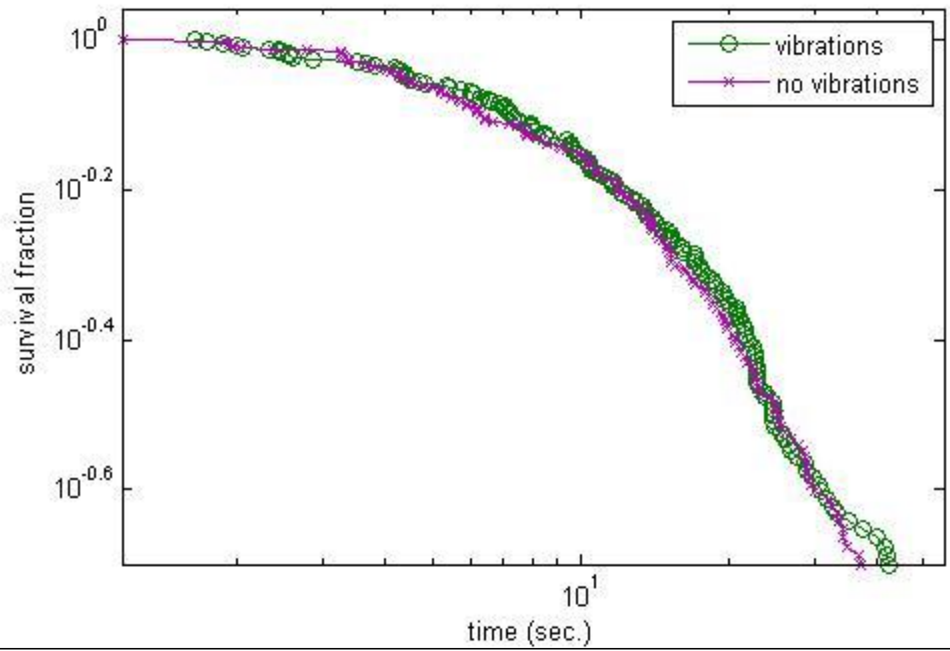
Figure 6. Overall survival curve all the trials (vibration and no vibration)—VG vs. CG. This graph displays the overall survival curves, consisting of data points from all the trials—with and without vibrations, for the Variable Group (VG) and the Control Group (CG). The VG's overall $T_{1/2}$ value is significantly larger than that of the CG ($P = 0.0021$; Rank Sum Test).

The Variable Group outperformed and achieved a higher wobble board balancing skill level than the Control Group in all conditions analyzed. The VG's larger $T_{1/2}$ value is reflected by the upward and rightward shifts in all of the Variable Group's survival curves, compared to those of the Control Group (Figure 4, Figure 5, & Figure 6). In turn, the VG's larger $T_{1/2}$ value indicates that the Variable Group acquired a greater skill in wobble board balancing than the Control Group. This phenomenon manifests itself across both environments employed: random trials with vibration (Figure 4) and those without vibration (Figure 5). Not only did the Variable Group maintain a higher $T_{1/2}$ value in each individual set of conditions (with vibrations: P = 0.0154, Rank Sum Test; without vibrations: P = 0.0500, Rank Sum Test), the Variable Group advanced to attain a higher cumulative $T_{1/2}$ value (Figure 6) for Experiment 2 (P = 0.0021; Rank Sum Test). This means that when the trials from both conditions—with and without vibrations—were combined to yield an overall $T_{1/2}$ value, the Variable Group was able to balance on the wobble board for an average of 5.7 seconds longer than the Control Group (Figure 6). For each analyzed set of data (vibration trials, non-vibration trials, and combined trials), the difference between the $T_{1/2}$ of the Variable Group and the Control Group was statistically significant.



$T_{1/2}$ VALUES FOR THE VARIABLE GROUP	
Vibrations trials (n = 420)	**Non-vibration trials (n = 420)**
33.1 s	28.7 s

Figure 7. Survival curve for the Variable Group—vibration vs. no vibration. The vibration and non-vibration survival curves for the Variable Group are displayed. The difference between the vibration and non-vibration $T_{1/2}$ values is not statistically significant (P = 0.287; Rank Sum Test). Each curve represents the 420 trials in which subjects from the VG participated for each condition.



$T_{1/2}$ VALUES FOR THE CONTROL GROUP	
Vibration Trials (n = 360)	**Non-vibration Trials (n = 360)**
25.6 s	24.8 s

Figure 8. Survival curve for Control Group—vibration vs. no vibration. The survival curves for trials with and without vibrations are compared within the Control Group. A sharp similarity is seen between the two survival curves. In fact, the $T_{1/2}$ value for the trials with vibration is not significantly larger than the $T_{1/2}$ value for the trials without vibrations ($P = 0.615$; Rank Sum Test).

In regards to intra-group comparisons, the group that learned and trained with vibrations (VG) did not benefit from the application of vibrations during Experiment 2 (Figure 7). However, the group's balance was not hindered when vibrations were removed (Figure 7), for the difference between the $T_{1/2}$ values for vibration and non-vibration is not statistically significant ($P = 0.615$; Rank Sum Test). The group that learned and trained without vibrations was also neither affected by the vibrations nor by the lack of vibrations (Figure 8); likewise, the difference between the vibration and non-vibration $T_{1/2}$ values were not significant for this group ($P = 0.615$; Rank Sum Test). In essence, aside from inter-group comparisons, there were no significant differences found from measuring the affects of vibration. Neither group's balance in Experiment 2 was improved by the random employment of vibrations during this experiment. This absence of effect within intra-group comparisons is made apparent by the lack of a major shift, in any direction, in the survival curves for the Variable Group (Figure 7) and the Control Group (Figure 8).

Comparisons Among Individuals

Subject Identification Number	Group from Experiment 1 (VG/CG)	$T_{1/2}$ for non-vibration trials (n = 30)	$T_{1/2}$ for vibration trials (n = 30)	$T_{1/2}$ improved with vibrations? (Y/N)
1	VG	14.7 s	19.9 s	Y
3	VG	19.7 s	18.6 s	N
5	VG	37.2 s	40.6 s	Y
8	VG	38.9 s	52.1 s	Y
9	VG	36.4 s	34.3 s	N
10	VG	41.6 s	51.8 s	Y
16	VG	12.5 s	13.3 s	Y
4	CG	28.1 s	33.2 s	Y
11	CG	32.5 s	33.6 s	Y
14	CG	24.4 s	27.7 s	Y
18	CG	33.0 s	21.8 s	N
20	CG	14.1 s	23.3 s	Y
21	CG	14.8 s	13.5 s	N

Table 4. Individual $T_{1/2}$ values after 30 trials of vibration and non-vibration. Each subject's $T_{1/2}$ value for their vibration and non-vibration trials in Experiment 2 is given. No individual displayed statistically significant differences between their $T_{1/2}$ values for the vibration trials and non-vibration trials (Rank Sum Tests were used significance testing of each individual's $T_{1/2}$ values—Subject 1: P = 0.0993; Subject 3: P = 0.7845; Subject 5: P = 0.6309; Subject 8: P = 0.1453; Subject 9: P = 0.947; Subject 10: P = 0.4161; Subject 16: P = 0.7338; Subject 4: P = 0.1334; Subject 11: P = 0.7506; Subject 14: P = 0.865; Subject 18: P = 0.0798; Subject 20: P = 0.2458; Subject 21: P = 0.8476).

On a local scale, little differences were found between an individual's $T_{1/2}$ value for vibration trials and his or her $T_{1/2}$ value for non-vibration trials (Table 4). A total of nine individuals from both groups showed a higher $T_{1/2}$ value for trials administered with vibrations in comparison to those ran without vibrations. Although the majority (9/13) of the individuals in Experiment 2 showed an improvement in wobble board balancing while vibrations were employed, no individual showed statistically significant differences between their vibration $T_{1/2}$ value and their non-vibration $T_{1/2}$ value. Similarly, the four individuals (Subjects 3, 9, 18, & 21), whose balance was impeded by vibrations, did not show any significant differences between their vibration $T_{1/2}$ value and their non-vibration $T_{1/2}$ value. Thus, the application of vibrations during wobble board balancing had no statistically significant effect on any individual subject.

DISCUSSION:

The results of this experiment did not yield the hypothesized results about the effect of vibrations on wobble board balancing; vibrations did not significantly affect one's wobble board balancing ability. However, the results of the experiment did suggest an important conclusion about vibration training: learning a motor skill such as wobble board balancing can be facilitated by vibrations.

Experiment 1 Conclusions

Results from Experiment 1 suggested two important conclusions: (i) learning a motor skill such as wobble board balancing is not expedited with the use of vibrations, and (ii) learning a motor skill is usually accompanied by a large increase in skill after a short amount of practice time. Since the Variable Group did not achieve the intermediate skill level faster than those in the Control Group (Figure 2), it appears that vibrations had no effect on the speed at which one acquires proficiency with a motor skill. Also, the nervous system exhibited a phenomenon similar to that of an action potential: a threshold effect. Small initial increases in skill, followed by large increases in skill—especially during the last two days of Experiment 1 (Figure 3), suggest that the nervous system will allow for a "jump" in skill level once one has achieved a certain threshold level, in terms of the amount of practice completed. Further, each training period, yielding larger $T_{1/2}$ values, represents small excitatory postsynaptic potentials (EPSPs) in this proposed analogy. Eventually, the amount of practice, or number of EPSPs, synergistically combines to reach the necessary threshold level, evoking a large improvement from a novice skill level to an intermediate one. However, the threshold level for attaining this "jump" is different for each person (Figure 2). So, developing a uniform rule correlating the exact amount of practice to the exact skill level would be nearly impossible. Instead, a more general principle—"more practice yields higher skill level"—can be supported by these results.

Skeptics may seek to invalidate these results by suggesting that the two groups were not equivalent at the beginning of each experiment. Not only is the initial skill level of the Variable Group higher, but there are more females, and more subjects overall in this group (Table 2). Upon further review, it was confirmed that the differences between the Control and Variable Groups in Experiment 1 (Table 2) were statistically insignificant in terms of the number of males and females in each group ($P = 0.9002$; Rank Sum Test), and the differences between each group's baseline $T_{1/2}$ value ($P = 0.7510$; Rank Sum Test). Therefore, comparisons between the two groups in Experiment 1 were validly conducted.

Experiment 2 Conclusions

The results of Experiment 1 could not be fully appreciated until the completion of Experiment 2, because the three statistically significant points extracted from Experiment 2 corresponded to the manner in which the participants learned to wobble board balance in Experiment 1. Since the Variable Group outperformed the Control Group in each comparable facet of Experiment 2 (Figure 4, 5, & 6), the results of Experiment 2 indicate vibration training as a crucial effector of performance. Learning a motor skill—such as wobble board balancing—while using vibrations, appears to elevate ones performance once one has acquired an above-novice level of skill. This conclusion is bolstered by the fact that the difference in $T_{1/2}$ values between the two groups at the beginning of Experiment 2 was statistically insignificant (P = 0.1807; Rank Sum Test). Thus, the two groups had equal baseline levels, but the Variable Group's previous training with vibrations allowed the group to outperform the Control Group. Moreover, it should also be noted that the difference in the number of males and females in each group was also statistically insignificant (P = 1.0; Rank Sum Test). Thus, the comparisons between the groups were also validly conducted in Experiment 2.

Other data from Experiment 2 led to the finding that the use of vibrations (50 Hz, 0.18 mm amplitude) does not improve the wobble board balancing skill of the Variable Group or the Control Group, regardless of whether individuals in the group learned the skill with vibrations or not (Figure 7 & 8). This conclusion is consistent with the fact that no individual subject had a statistically significant difference in performance between trials with and without vibrations, irrespective of whether he or she was part of the Control or Variable Group in Experiment 1 (Table 4). The contrast between this conclusion, and that found by Milton *et. al.* (2009b), does not necessarily show that vibrations do not improve one's performance in a wobble board balancing task. Instead, the discrepancy merely shows that the specific set of conditions used (50 Hz, 0.18 mm amplitude) does not improve one's wobble board balancing skill. This perspective allows for further investigations in the matter; there are a myriad of different combinations of vibrational amplitudes and frequencies that were not tested in this thesis—simply changing one or the other, or both, could potentially yield different results. Nonetheless, examining how vibrations affect the body will continue to be difficult, as shown by the conflicting results of Moran *et. al.* (2007), who concluded that vibrations did not enhance neuromuscular performance during or immediately after training, and that of Torvinen *et. al.* (2002), who showed that muscle performance transiently improved after the application of vibrations. Each person's body is different, and thus, each person's body will respond differently to vibrations.

Overall Conclusions Summary

Examining the results of Experiment 1 and 2 in tandem suggests several overall conclusions. First, the results provide evidence that vibrations do not accelerate the speed at which one learns to balance on a wobble board, or ride a unicycle. Second, the physical effects of vibrations do not enhance the skill with which one balances on a wobble board or rides a unicycle, unlike stick balancing. Third, the results suggest that vibrations can somehow bear a positive influence on the neural connections formed while learning a motor skill, thereby enhancing ones skill. In this third conclusion, one's skill is only enhanced compared to those who did not learn to wobble board balance with vibrations. However, the physical vibrations themselves still had no affect on an individual's performance, compared against his or her own trials with and without vibrations.

Proposed Explanations for the Reached Conclusions

Determining the exact neural cause of the conclusions suggested by the data from Experiment 1 and Experiment 2 would be difficult due to the time, money, and technological limitations faced while conducting this thesis. Nevertheless, I propose a couple of hypotheses to help explain the neuroscience behind the results. First, in Experiment 1, I postulate that the learning curve latency before the large “jump” in skill could represent the time it takes to establish “fast learning” neural pathways. These pathways are formed during the initial learning phase when acquiring a new motor skill (Karni *et. al.*, 1998). For Experiment 2, I propose that learning a motor task in the presence of vibrations results in larger representations of movements in maps in the primary motor cortex, as suggested by Karni *et. al.* (1998) while analyzing a similar experiment in which monkeys learned a novel motor task (Nudo *et. al.*, 1996). Should this be true, I propose that the establishment of these broader and more extensive neural pathways during the use of vibrations could also be used for simpler tasks, such as wobble boarding without vibrations. This would allow the Variable Group to claim a better performance than those who learned to wobble board balance without vibrations (as seen in Figure 5, 6, & 7). Those in the Control Group would not be able to call upon the same type of pathways exploited by the Variable Group, since the CG would not have established as voluminous or complex neural pathways. The principle arrived at here corresponds to the commonly accepted principle of exercise training, where practicing under more strenuous conditions will lead to better performance. For example, training for a marathon at higher altitudes, where there is less oxygen, would result in a better performance when the actual race was at sea level, where oxygen is plentiful. Also corresponding to this hypothesis is the a principle offered by Fairweather (1997), as he suggests that training in more variable conditions will also yields a better performance during the “real game.”

Future Considerations

Despite my proposed explanations for the results in our experiment, it must be underscored that these proposals are only preliminary hypotheses. Much more research must be conducted in order to prove or disprove my hypotheses. Further, improvements to the experiment could be made to make my hypotheses stronger, or weaker. For instance, our sample size (n = 21) was far too small to apply our conclusions to a whole population of Japanese students learning to ride unicycles. On top of that, the age range (college students) of our sample group was much higher than the age group with which we wish to apply our conclusions (elementary school students). Perhaps the children learning how to ride unicycles are more pliable and able to absorb vibrations better than college students. Additionally, noise-cancelling headphones could have been utilized to eliminate the effect that the loud rumbling noise made by the Globus Physioplate; the noise could have impacted concentration levels in participants. Also, many of the participants had lower trial times at the beginning of each training or testing period. This can potentially be nullified with a few warm-up trials, allowing the subjects’ muscles to be “woken up” and primed for performance. Another portion of our experiment that could have been changed to improve the authenticity of our results was the manner in which we interacted with our participants. It was reported that some participants felt awkward performing balancing movements in front of complete strangers; so, these participants may have self-consciously restricted their movements and stunted their potential. Also, I propose that it could have been possible for participants to induce autonomic activity (Lee *et. al.*, 1996; Roure *et. al.*, 1998), as they prepare themselves for balancing with the vibrations. This increase in autonomic activity, or the “flight or fight” response, is known to produce physiological changes that allow one to maximize ones physical performance. Finally, since increasing the bend at the knees reduces the stiffness of one’s body and increases the amount of shock absorption (Lafortune *et. al.*, 1996), the degree to which the knees were bent could have standardized. Thus, future studies should take into account the mentioned variables above.

ACKNOWLEDGEMENTS

First, I would like to thank Professor John Milton for all his help and support throughout the year. His aid and insight really helped guide my thesis project to completion. Additionally, I would like to thank Rachel Dajani and Emily Deyoe for their time and cooperation during the whole experiment. Without any of them, this thesis would not have been possible. Lastly, I would like to thank my friends and family for their support and encouragement.

REFERENCES

Benzi, R. Sutera, A., & Vulpiani, A. 1981. “The mechanism of stochastic resonance.” *J. Phys. A: Math. Gen.* 14: L452-L-457.

Berg, K.O., Wood-Dauphinee, S.L., Williams, J.I., & Maki, B. 1992. “Measuring balance in the elderly: validation of an instrument. *Can. J. Public Health.* 83 Suppl 2: S7-11.

Cabrera, J.L., & Milton, J.G. 2002. “On-Off Intermittency in a Human Balancing Task.” *Physical Review Letters*. 89(15): 158702-1 – 158702-4.

Cabrera, J.L, & Milton, J.G. 2004. “Human stick balancing: Tuning Lévy flights to improve balance control.” *Chaos.* 14(3): 691-698.

Cardinale, M., & Pope, M.H. 2003. “The effects of whole body vibration on humans: Dangerous or advantageous?” *Acta Physiologica Hungarica*. 90(3): 195-206.

Casadio, M., Morasso, P.G., & Sanguineti, V. 2005. “Direct measurement of ankle stiffness during quiet standing: implications for control modeling and clinical application.” *Gait Posture* (in press).

Englander F, Hodson TJ, & Terregrossa, RA. 1996. “Economic dimensions of slip and fall injuries.” *Journal of Forensic Science*. 41(5):733–46

Fairweather, M. 1999. “Skill learning principles: implications for coaching practice.” *The Coaching Process: Principles and Practice*. Butterworth Heinemann. Oxford, UK.

Fuller, G.F. 2000. “Falls in the elderly.” *Am. Fam. Physician.* 61(7): 2159-2168, 2173-2174.

Gage, W.H., Winter, D.A., Frank, J.S., & Adkin, A.L. 2003. “Kinematic and kinetic validity of the inverted pendulum model in quiet standing.” *Gait and Posture*. 19: 124-132.

Garg, D.P., & Ross, M.A. 1976. “Vertical Mode Human Body Vibration Transmissibility.” *Transactions on Systems, Man, and Cybernetics*. SMC-6(2)102-112.

Griffin, M.J. 1981. “Biodynamic Response to Whole-Body Vibration.” *The Shock and Vibration Digest*. 13: 3-12.

Gyorffy, J. 2009. “Effects of Vibration on Postural Sway.” Joint Science Department of the Claremont Colleges, Senior Thesis. Claremont, CA.

Ivanenko, Y.P., Grasso, R., Israel, I., & Berthoz, A. 1997. “The contribution of otoliths and semicircular canals to the perception of two-dimensional passive whole-body motion in humans.” *Journal of Physiology.* 502(1): 223-233.

Ivanenko, Y.P., Grasso, R., & Lacquaniti, F. 2000. "Influence of Leg Muscle Vibration on Human Walking." *Journal of Neurophysiology*. 84:1737-1747.

Jordan, J.M., Norris, S.R., Smith, D.J., & Herzog, W. 2005. "Vibration Training: An Overview of the Area, Training Consequences, and Future Considerations." *Journal of Strength and Conditioning Research*. 19(2): 459-466.

Karni, A., Meyer, G., Rey-Hipolito, C., Jezzard, P., Adams, M.M., Turner, R., & Ungerleider, L.G. 1998. "The acquisition of skilled motor performance: Fast and slow experience-driven changes in primary motor cortex." *Proc. Natl. Acad. Sci. USA.* 95: 861-868.

Kiiski, J., Heinonen, A., Järvinen, T.L., Kannus, P., & Sievänen, H. 2008. "Transmission of Vertical Whole Body Vibration to the Human Body." *Journal of Bone and Mineral Research*. 23. DOI: 10.1359/jbmr.080315

Kuo, A.D. 1993. "An Optimal Control Model for Analyzing Human Postural Balance." *IEEE Transaction on Biomedical Engineering*. 42(1): 87-101.

Lafortune, M.A., Lake, M.J., & Hinnig, E.M. 1996. "Differential shock transmission response of the human body to impact severity and lower limb posture." *Journal of Biomechanics*. 29(12): 1531-1537.

Lee, L.H., & Olness, K.N. 1996. "Effects of self-induced mental imagery on autonomic reactivity in children." *Journal of Developmental and Behavioral Pediatrics*. 17(5): 323-327.

Loram, I.D., & Lakie, M. 2002. "Human balancing of an inverted pendulum: position control by small, ballistic-like, throw and catch movements." *Journal of Physiology*. 540(3): 1111-1124.

Matsumoto, Y., & Griffin, M.J. 1998. "Dynamic response of the standing human body exposed to vertical vibration: influence of posture and vibration magnitude." *Journal of Sound and Vibrations.* 212(1): 85-107.

Maurer, C., Mergner, T., Bolha, B., & Hlavacka, F. 2001. "Human balance control during cutaneous stimulation of the plantar soles." *Neuroscience Letters*. 302: 45-48.

Milton, J., Townsend, J.L., King, M.A., & Ohira, T. 2009. "Balancing with positive feedback: the case for discontinuous control." *Philosophical Transaction of the Royal Society A.* 367: 1181-1193.

Milton, J.G., Ohira, T., Cabrera, J.L., Fraiser, R.M., Gyorffy, J.B., Ruiz, F.K., Strauss, M.A., Balch, E.C., Marin, P.J., & Alexander, J.L. 2009. "Balancing with Vibration: A Prelude for 'Drift and Act' Balance Control." *PLoS ONE.* 4(10): e7427. Doi: 10.1371/journal.pone.0007427.

Moran, K., McNamara, B., & Luo, J. 2007. “Effect of Vibration Training in Maximal Effort (70% 1RM) Dynamic Bicep Curls.” *Medicine & Science in Sports & Exercise*. 39(3): 526-533. DOI: doi: 10.1249/mss.0b013e31802d11a7

Morton, S.M., & Bastian, A.J. 2004. “Cerebellar Control of Balance and Locomotion.” *Neuroscientist*. 10: 247-259

Nudo, R.J., Milliken, G.W., Jenkins, W.M., & Merzenich, M.M. 1996. “Use-Dependent Alterations of Movement Representation s in Primary Motor Cortex of Adult Squirrel Monkeys.” *Journal of Neuroscience*. 16(2): 785-807.

Padua, D.A., Arnold, B.L., Perrin, D.H., Gansneder, B.M., Carcia, C.R., & Granata, K.P. 2006. “Fatigue, Vertical Leg Stiffness, and Stiffness Control Strategies in Male and Females.” *Journal of Athletic Training.* 41(3): 294-304.

Purves, D., Augustine, G.J., Fitzpatrick, D., Hall, W.C., LaMantia, A., McNamara, J.O., & White, L.E. 2008. *Neuroscience*. Fourth Ed. Sinauer Associates Inc. Sunderland, MA.

Proske, U., Morgan, D.L., & Gregory, J.E. 1993. “Thixotropy in skeletal muscle and in muscle spindles: a review.” *Progress in Neurobiology*. 41: 705-721.

Rasmussen, G. 1983. “Human body vibration exposure and its measurement.” *J. Acoust. Soc. Amer*.73: 2229.

Redfern, M.S., Yardley, L., & Bronstein, A.M. 2001. “Visual influences on balance.” *Anxiety Disorders*. 15: 81-94.

Roure, R., Collet, C., Deschaumes-Molinaro, C., Dittmar, A., Rada, H., Delhomme, G., & Vernet- Maury, E. 1998. “Autonomic nervous system responses correlate with mental rehearsal in volleyball training.” *European Journal of Applied Physiology and Occupational Physiology.* 78(2): 99-108.

Skoyles, J.R. 2006. “Human balance, the evolution of bipedalism and disequilibrium syndrome.” *Medical Hypotheses*. 66: 1060-1068.

Sorensen, K.L., Hollands, M.A., & Patla, A.E. 2002. “The effects of human ankle muscle vibration on posture and balancing during adaptive locomotion.” *Experimental Brain Research.* 143:24-34.

Stevens, J.A., Corso, P.S., Finkelstein, E.A., & Miller, T.R. The costs of fatal and nonfatal falls among older adults. Injury Prevention 2006; 12:290–5

Tideiksaar, R. 1988. “Falls in the Elderly.” *Bulletin of the New York Academy of Medicine*. 62 (2):145-163.

Torvinen, S., Kannus, P., Sievänen, H., Järvinen, T.A.H., Pasanen, M., Kontulainen, S., Järvinen, T.L.N., Järvinen, M., Oja, P., & Vuori, I. 2002. "Effect of a vibration exposure on muscle performance and body balance. Randomized cross-over study." *Clinical Physiology and Functional Imaging*. 22(2): 145-152.

Wang, L. 2009. "Bridging Postural Sway and Stick Balancing Using an Inverted Pendulum." Joint Science Department of the Claremont Colleges, Senior Thesis. Claremont, CA.

Winter, D.A., Patla, A.E., Prince, F., Ishac, M., & Gielo-Perczak, K. 1998. "Stiffness Control of Balance in Quiet Standing." *Journal of Neurophysiology*. 80: 1211-1221.

Wolfson, L.I., Whipple, R., Amerman, P., Kaplan, J., & Kleinberg, A. 1985. "Gait and balance in the elderly. Two functional capacities that link sensory and motor ability to falls." *Clin. Geriatr. Med.* 1(3): 649-59.

www.web-japan.org, 1998. "Unicycles."

Appendix I: Participant Questionnaire

Name: ___________________________________

Age: _______ Gender: _______

Email Address: ________________________________

Phone Number: ________________________________

1. Do you play any sports?

Yes No (circle one)

If yes, please specify which sports.

2. Have you sustained any injuries to your legs (sprains, fractures, breaks)?

Yes No (circle one)

If yes, please specify what and how long ago the injury occurred.

3. Have you ever participated in sports requiring above average balance (e.g. gymnastics, surfing, skateboarding, slack lining, and unicycle riding). Please specify the activity.

If yes, do you currently participate? Yes No (circle one)

How long have you/were you involved in the activity?

How long ago did you stop participating in the activity?

4) How often to you exercise? What type of exercise do you do (e.g. cardio, strength training)?

Appendix II: *SurvivalCurve.m*

```
function SurvivalCurve(x)

mean(x)

x1=sort(x);
median(x)

t=(length(x):-1:1)';
loglog(x1,t/length(x),'ko-')
axis([0 55 0.2 1.1])
ylabel('survival fraction')
xlabel('time (sec.)')
```

Appendix III: *mikevib.m*

```
%%%Generates random sequences of vibration/non-vibration trials
%%ratio of vibration/nonvibration trials = 1:1

function [n] = mikevib(x) %%input x to return x number of trials

m = randperm (x);          %% generates random sequence

for n = mod(m,2) %%converts sequence into binary code based even/odd


   if n == 0                %% if even, return "VIBRATION"
       disp('VIBRATION');

   else           %% if odd, return "NONE" - signifying no vibration
       disp('NONE');

   end

end

end
```