THE PENNSYLVANIA STATE UNIVERSITY
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POSTURAL PERTURBATION PRODUCED BY OPTIC FLOW

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Abstract

When considering diagnostic measures of traumatic brain injury, virtual reality tests that are sufficiently sensitive enough to reveal subclinical residual effects may help to determine if a concussed athlete is indeed ready to return to play. A series of pilot studies relating postural coherence and optic flow contributed to the design of a specific protocol intended to supplement return to play protocols. The preliminary protocol focused on the creation of a visual pulse introduced in a virtual reality setting originating from Lee's moving room paradigm. Foot stance and phase of the pulse introduced were varied to investigate the effects on postural stability. After concluding that the Romberg stance and out of phase pulses maximally induce postural instability, a specific protocol involving three asymptomatic students aimed to test the effects of varying pulse frequency and predictability on time to recovery of postural coherence. Pulse frequencies of 0.2 and 0.4 Hz were found to induce the longest time to recovery of postural coherence and thus will be utilized in the development of future studies comparing TBI subjects. Specifically, clinical implications involve the implementation of the specific protocol into current return to play protocols.

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Acknowledgments

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Chapter 1

Introduction

Statement of the Problem

Knowing whether a concussed patient has recovered sufficiently to safely resume normal activity is a critical topic of discussion in the field of sports medicine. In the scope of athletics, an athlete's readiness to return-to-play is not always clear-cut. Concussions are complex injuries caused by blows to the head that are often difficult to diagnose and treat. They are unlike any other injury to the body. While broken bones can be detected through X-rays, concussions on the other hand present themselves more ambiguously and frequently involve effects that are not always easily perceived by the patient or the doctors treating them. It is arduous to know how an individual will be affected by a concussion and how long their recovery process will take. Being restricted from athletic participation can be frustrating for a concussed athlete, especially if he or she feels asymptomatic. Yet, residual subclinical effects can pose a threat to a patient's safety if he or she returns to activity too soon. Many of the recent clinical tests used to scale the severity of a concussion are based on loss of consciousness and any physical or emotional symptoms perceived by a patient, which are not always indicative of the injury.[1]

There is a great need for clinical tests that are sensitive enough to reveal these subclinical residual effects. Inadequacy in standard balance testing is supported in current research by Slobounov, Tutwiler, Sebastianelli et al., stating how patients who are tested by the standard balance testing pass just 10 days after injury, making it seem as though they are recovered.[1] However, given a more dynamic balance test that induces postural instability with optic flow, those same patients were still displaying deficiency of postural stability 30 days after injury. Thus, the use of virtual reality systems in a clinical setting can provide a more sensitive means for testing postural stability in concussed individuals than the standard balance testing.

Nearly every task of living relies on having adequate postural stability. Previous research has shown that this ability is affected by factors such as old age and traumatic brain injury.[1,3,4] Specifically, athletes who are affected by a traumatic brain injury (TBI) may also suffer decreased performance and increased risk of injury in sport due to their diminished postural stability. This is especially important given the dynamic and often unpredictable nature of sport that requires an athlete to maintain balance at any given moment. Athletes who have been afflicted by TBI and who return to play before they have fully recovered not only risk decreased performance but also risk an increased chance of suffering second-impact syndrome due to residual effects. Current research models have demonstrated how concussed athletes, who may have previously been cleared to return to play by older clinical concussion tests, could still be suffering more covert neurological effects. [1]

Ted Johnson, a professional football player of the New England Patriots, had suffered many concussions throughout his career. Now that his career is over, he still faces the effects of the damage caused by the injuries to his brain. “Johnson said he played through concussions because he, like many other NFL athletes, did not understand the consequences. He has publicly criticized the NFL for not protecting players like him.”[7] Doctors thus face the important responsibility of deciding when a concussed patient is truly ready to return to play to protect athletes like Ted Johnson from serious long-term effects.

This example demonstrates how an athlete may be able to pass the current clinical concussion tests, yet such criteria may not be revealing the subclinical residual balance effects of a concussion.[1] "Disruption of various CNS functions responsible for postural stability" may explain these balance deficits in those who have suffered from a concussion.[1] This study suggests that athletes may be returning to play sooner than they are ready based off of decisions made by clinical tests that may not be sensitive enough. There is a great need for clinical tests that are not only sensitive enough to pick up on the disturbed neurological effects of a concussion, but also diagnose an individual in a dynamic, and thus realistic, environment. The use of virtual reality as a diagnostic tool in concussions has been used effectively in prior research to detect residual effects of concussed individuals who otherwise would have been cleared for play.[2] Specifically, optic flow, created by perceived motion, is produced by a virtual moving room creates a realistic and controlled environment to test postural stability.[2]

The human body maintains postural stability from afferent cues from many sensory mechanisms working together, including "the vestibular system, muscle and join receptors, and vision." [6] Dijkstra et al. describe postural stability as a dynamic system and that postural stability is an "attractor solution," where all of the different sensory cues play a role in maintaining postural stability.[5] Furthermore, according to prior assessment, Asten, Gielen, Denier can der Gon claim that vision seems to be the dominant mechanism when assessing the body's orientation to its environment, based off of studies stemming from Lee's moving room paradigm.[6] Adamcova and Hlavacka found related results after investigating proprioceptive mechanisms of postural stability, noting that indeed "vision plays an important role in the maintenance of postural stability."[9] Likewise, Haibach, Slobounov, and Newell agree that "the visual system most often determines postural motion" based off of prior studies conducted by Lestienne, Soechting, Berthoz as well as the initial studies regarding optic flow conducted by Lishman and Lee.[4] This well supported assertion for vision being a dominant mechanism in postural stability has been utilized by means of applications in virtual reality in manipulating postural motion.[1,2,3,4,5,6,8,10]

In this study, virtual reality will serve as the means of inducing optic flow to subjects to provoke postural instability. While many studies have used a continuously moving virtual moving room to analyze postural stability,[1,2,3,4,5,6,8,10] the introduction of a visual pulse in a continuously moving virtual room is an innovative method of balance testing studied recently by researchers.[3,5] The effect of changing the frequency of a visual perturbation is a novel concept that has not yet been analyzed. Likewise, the predictability of the timing of such a visual perturbation is also a novel area of interest.

Before these specific questions could be examined, a series of pilot studies were conducted to determine the preliminary conditions that would be used in the specific protocol of the experiment: the nature of the pulse (in terms of a benchmark frequency and amplitude), foot stance, and phase of the pulse. The set of virtual reality conditions introduced above that would simultaneously increase the probability of postural instability in a virtual reality setting with asymptomatic subjects are first determined in the preliminary protocol. After determining these preliminary conditions, the specific protocol of determining the effect of the predictability and frequency of a pulse could then be examined.

Objectives

The conditions that were considered for the design of the preliminary protocol included the amplitude and frequency of a benchmark pulse, the foot stance of the individual during the movement (Romberg vs. bipedal), and the effects of the phase of the pulse (introduced in phase vs. out of phase). For each of these factors, the condition that created the longest adaptation time, in regards to returned coherence of movement, was of interest. The conditions that were found to induce the most postural instability were then used in the specific protocol to test the effects of varying pulse frequencies and the predictability of such pulses. The establishment of a unique visual method of data analysis that would depict time to recovery of postural coherence was implemented. This method would visually depict the coherence of the subject's movement to the movement of the virtual room. The gap in coherence created by the pulse, and thus the postural perturbation of the subject, allows for the time to recovery of postural coherence to be efficiently analyzed. The time to recovery data would be used with the intention for use as an additional component to future return-to-play testing protocols.

Preliminary Aims of the Project:

1. Define a benchmark amplitude and frequency for a visual perturbation that would induced postural instability
2. Compare stability in two different stances: Romberg vs. bipedal
3. Compare the effects of two different phases of a visual perturbation: introduced in phase vs. out of phase

Specific Aims of the Project:

4. Compare the effect of various frequencies of a visual perturbation
5. Compare predictable vs. unpredictable perturbations
6. Establish a novel means of visual data display and analysis intended for clinical implications

Overview

Chapter 2 describes the complete methodology that was followed in terms of the subjects tested, apparatuses, protocols, and the means of data processing and analysis. Chapter 3 includes the results of the project. Chapter 4 includes a discussion of the results and the limitations and the implications of the work.

Chapter 2

Methodology

Participants

There were 3 participants selected for the specific protocol, 2 males and 1 female. They were all students from The Pennsylvania State University. These subjects signed an Informed Consent Form for Biomedical Research prior to testing. Individuals who were experiencing any type of injury, such as ankle instability, as well as those who had uncorrected vision were excluded from this study. The subjects chosen were naïve to the pulse protocol, but understood that their balance would be tested in a virtual reality setting.

Apparatus

The physical setup of this study resembled that of the 2008 study by Haibaich et al. The force plate used was an Advanced Mechanical Technology Inc. platform (OR6-1000) and was connected t a DELL PRECISION 530 Linux PC workstation by a 16-bit analog-digital conversion-board. For the purpose of this particular study, the postural movement data from the platform was collected in two movements: Anterior-Posterior (Fy) and Medio-lateral (Fx). The sample rate used was 50 Hz with the excitation voltage set to 5V. Pulse Room software was created by for this study by InnovativeVR, LLC. Participants stood 2.5 feet away from a 4'x 5' screen that was positioned 60 degrees from the floor with the visual stimulus projected from a rear-projection system manufactured by Fakespace Systems. Surrounding the screen were two black curtains to each side. A IS900 device and wand that coordinated force plate input started the Pulse Room motion sequence and timer. This system started to actively capture and record subject data from the IS900. The actual visual stimulus depicted a room with two lateral walls consisting of parallel stripes, a ceiling consisting of horizontal stripes, a floor consisting of horizontal stripes, and a central wall consisting of vertical stripes. All stripes were black and yellow forming a virtual room with a height of 4', width of 5', depth of 6' in a window size of 1400x1050. 3.3 oz. CrystalEyes stereo glasses were worn by subjects and fit to head with a connective head strap if needed for fit. An adjustable custom-made harness was fitted to each subject and clipped to a sturdy ceiling beam as a safety precaution.

Preliminary Protocol

Subjects, after signing a cautionary waiver, were instructed to take off their shoes as the devices were fit to the subject. The motion tracking sensor belt was fit snugly to the body to ensure accurate data collection of the subject's movement. The safety harness was adjusted and clipped to the subject to prevent injury resulting from a loss of balance. The stereo glasses were given to the subject and held in place by a neck strap if necessary to warrant a proper fit.

For the preliminary pilot studies each trial lasted 30 seconds and the room would move continuously at a frequency of 0.2 Hz. During this 30-second trial, a pulse of frequency 0.65Hz and amplitude of +1.8 m randomly disrupted the continuous movement at any given point in time. Subjects were instructed to stand in the center of the force plate in the instructed stance: either bipedal or Romberg. For the bipedal stance, subjects were told to stand comfortably with their feet shoulder width apart. For the Romberg stance, subjects were told to put one foot directly in front of the other and that they could choose the foot which they put in front of the other. Subjects were instructed to look straight ahead at the screen directly in front of them and to follow the movement of the virtual room during a practice trial. After the practice trial, subjects were introduced to a set of 30 randomly timed pulses, 15 while in the bipedal stance and then 15 while in the Romberg stance.

To test the effect of in phase pulses, the subjects were introduced to a pulse at a point in the 30 second trial where the room was moving in an anterior fashion while the direction of the pulse coincided with the direction of the room, thus resulting in an in-phase effect. Likewise, subjects were introduced to the same pulse at a point in time when the room was moving in a posterior fashion would produce an out of phase effect. The time for the out of phase condition in these pilot studies coincided with the 10-second mark, whereas the in phase condition coincided with the 12.5-second mark.

The above preliminary protocol established the conditions that would be used in the specific protocol. In the specific protocol, the effects of different pulse frequencies, while using the same amplitude of + 1.8 m, and the predictability of the visual perturbation were tested.

Specific Protocol

To test the effect of various pulse frequencies and the predictability of the pulse, the following specific protocol was conducted. Three asymptomatic baseline subjects were told to move their bodies, with their feet in the Romberg stance, in the direction of the room and to match its cadence. The specific protocol used a pulse with an amplitude of +1.8 m, with varying frequencies (0.2, 0.4, 0.6, 0.8, 1.0 Hz) with 3 trials of each that interrupted the continuously moving room of frequency 0.2Hz. One 30 second practice trial was presented to the subjects to ascertain understanding of the task. A total of 30 different trials were presented to the subjects: 15 trials were presented in the unpredictable condition and 15 trials were presented in the predictable condition. The unpredictable condition, presented first, contained a visual perturbation that occurred at random times that coincided with an out of-phase effect. The predictable condition always introduced the visual perturbation at the 12.5 seconds. In between each 30 second trial, subjects were instructed by the cue "curtain" to obtain a comfortable stance and face the black curtain, located 90 degrees to the screen, for 10 seconds. After this 10 second break, the cue "screen" was given, signaling the subject to turn to look at the screen and again return to the instructed stance to prepare for another 30 second trial. This process was repeated until all 30 trials had been administered.

Data Processing/ Analysis

Kinematic data collected using Intersense Ultra sound system motion tracking. A MATLAB code was used to display the movement of the Pulse Room to the movement of the subject by representation of sinusoidal graphs. See Figure 1. Specifically, a custom made Wavelet code was written to visually represent the coherence of the subject's movement to the movement of the Pulse Room. A gap in coherence of postural movement in the Wavelet display represented the occurrence of the pulse. The time to recovery of postural coherence is quantified by measuring the length of the distance of the coherence gap in the Wavelet illustration. A larger gap represents a longer time to recovery. The defining borders of each gap were defined by the median color value of each illustration. After determining the color that would correspond to the starting and ending borders of the gap, the distance was calculated by the difference in the X value of these two gap edges. These values were then plotted with a linear regression relating frequency and time to stability.

Chapter 3

Results

1. Define parameters of a visual perturbation that would induce loss of balance from baseline individuals

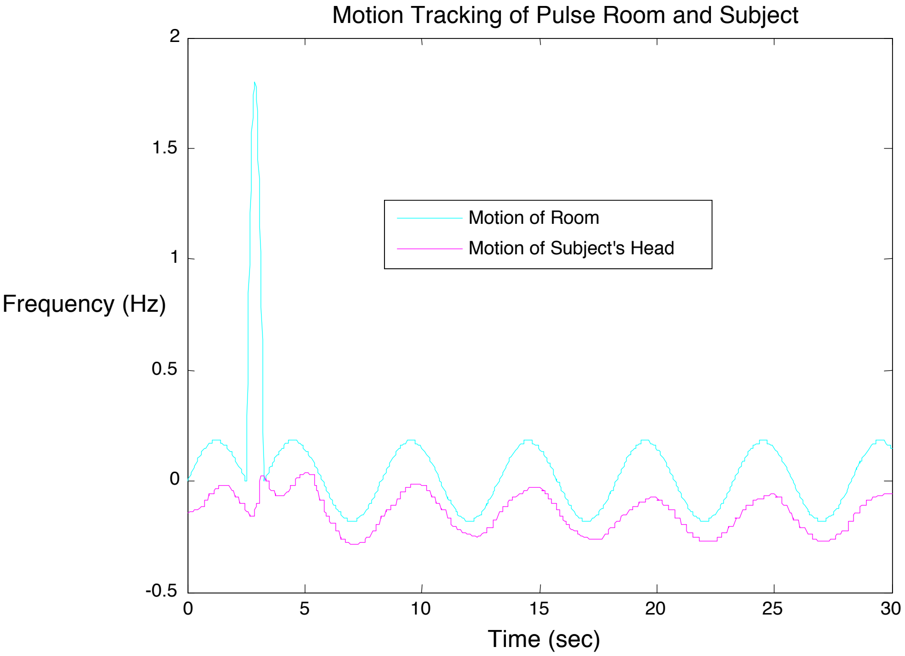

Figure 1: Pilot study displaying that a pulse with an amplitude of + 1.8 m and frequency of 0.65 Hz induces postural instability

Figure 1 illustrates the movement of the room (blue) compared to the movement of the subject's head (magenta). A visual pulse, with amplitude +1.8 m and frequency 0.65 Hz, interrupts the rhythm of the virtual room at 2.5 seconds, moving at 0.2 Hz. This figure thus depicts the successful physical perturbation of the subject induced by the pulse.

2. Compare loss of balance due to a perturbation in two different stances, Romberg vs. bipedal

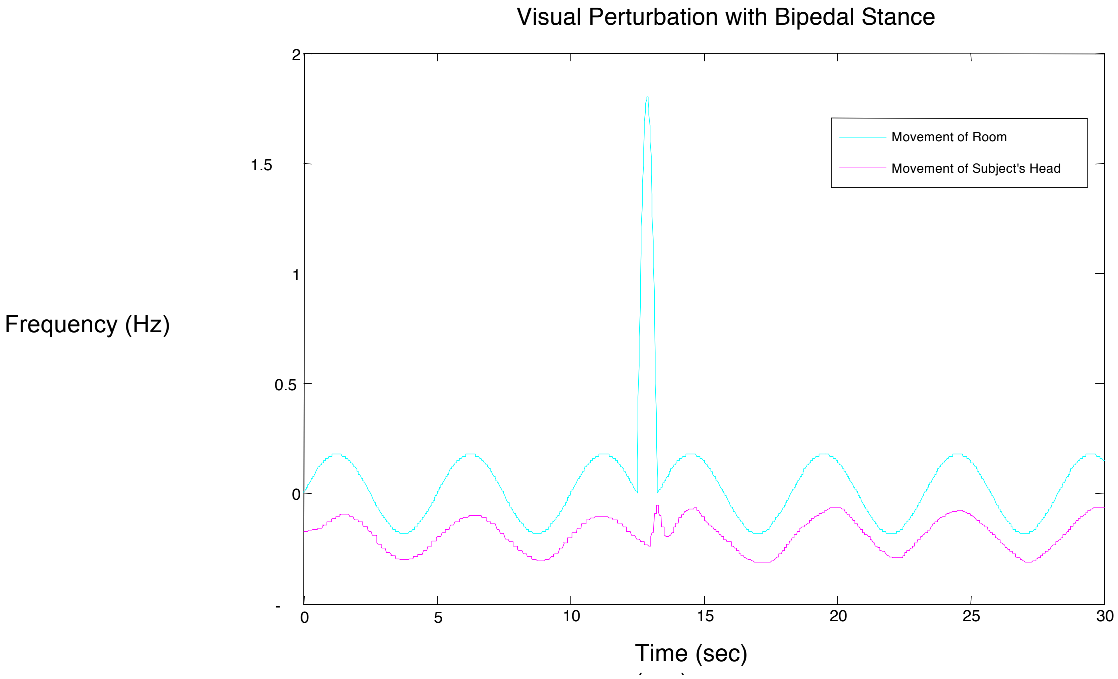

Figure 2: Pilot study displaying a pulse introduced while the subject is in a bipedal stance

Figure 2 illustrates the movement of the room (blue) compared to the movement of the subject's head (magenta). A visual pulse, with amplitude +1.8 m and frequency 0.65 Hz, interrupts the rhythm of the virtual room at 12.5 seconds, moving at 0.2 Hz. This figure depicts a moderate perturbation induced by the pulse while the subject is in a bipedal stance.

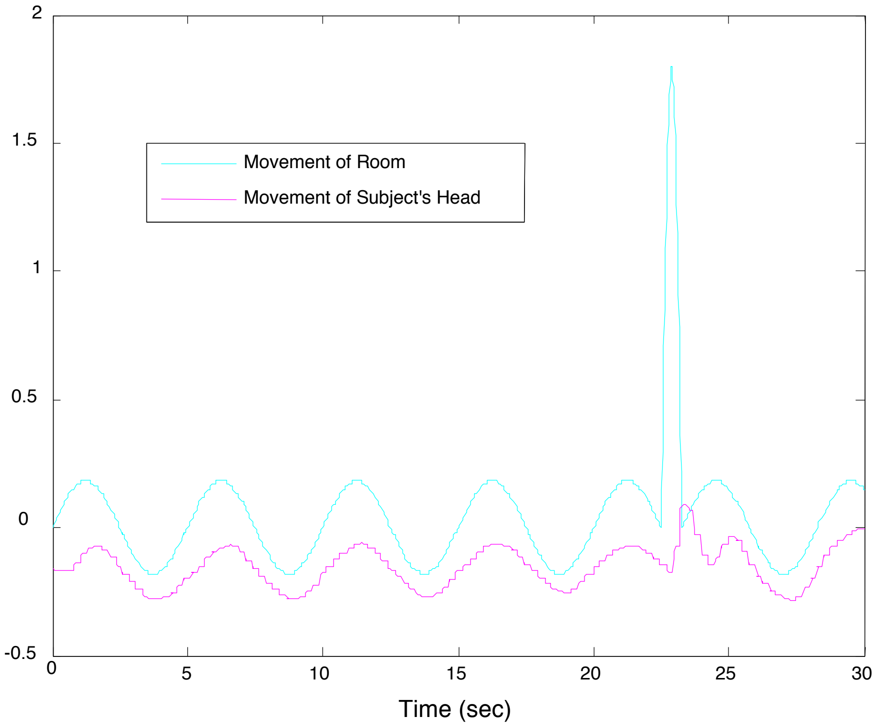

Figure 3: Pilot study displaying a pulse while the subject is in the Romberg stance

Figure 3 illustrates the movement of the room (blue) compared to the movement of the subject's head (magenta). A visual pulse, with amplitude +1.8 m and frequency 0.65 Hz, interrupts the rhythm of the virtual room at 22.5 seconds, moving at 0.2 Hz. This figure depicts a moderate-pronounced perturbation induced by the pulse while the subject is in a Romberg stance.

3. Compare effects of a pulse introduced in phase vs. out of phase

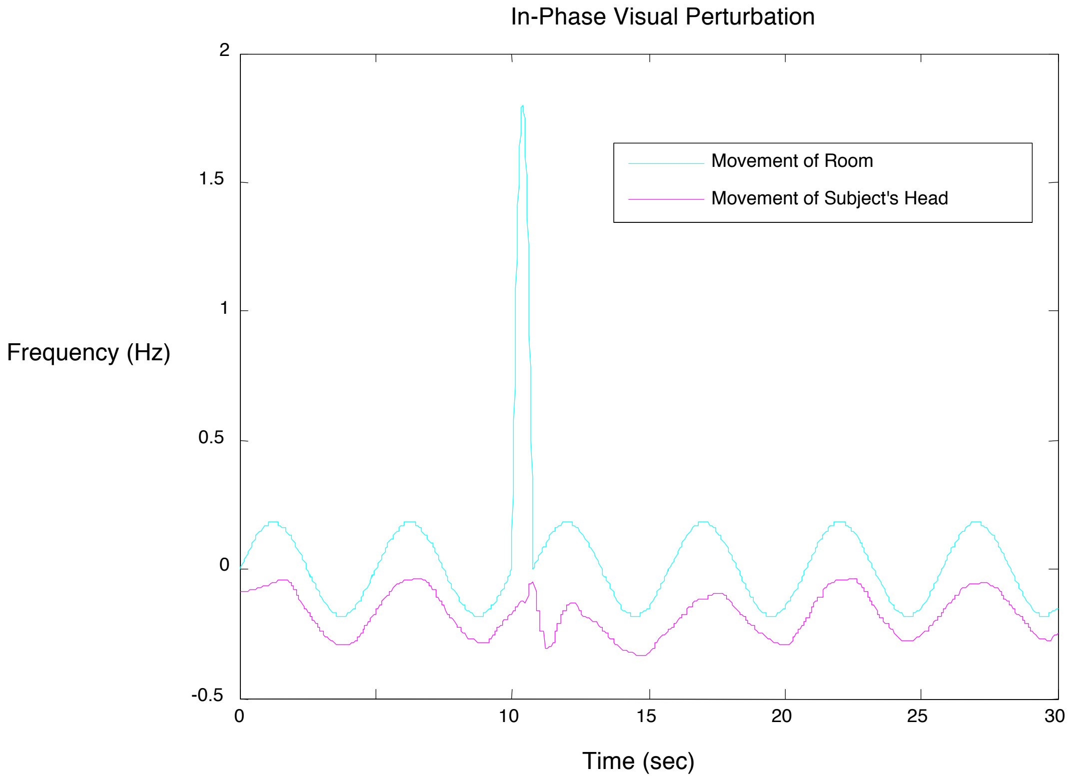

Figure 4: Pilot study displaying a pulse introduced in phase to the movement of the room while the subject is in the Romberg stance

Figure 4 illustrates the movement of the room (blue) compared to the movement of the subject's head (magenta). An in phase visual pulse interrupts the rhythm of the virtual room at 10.0 seconds, moving at 0.2 Hz. This figure depicts a moderate perturbation induced by the pulse while the subject is in a Romberg stance.

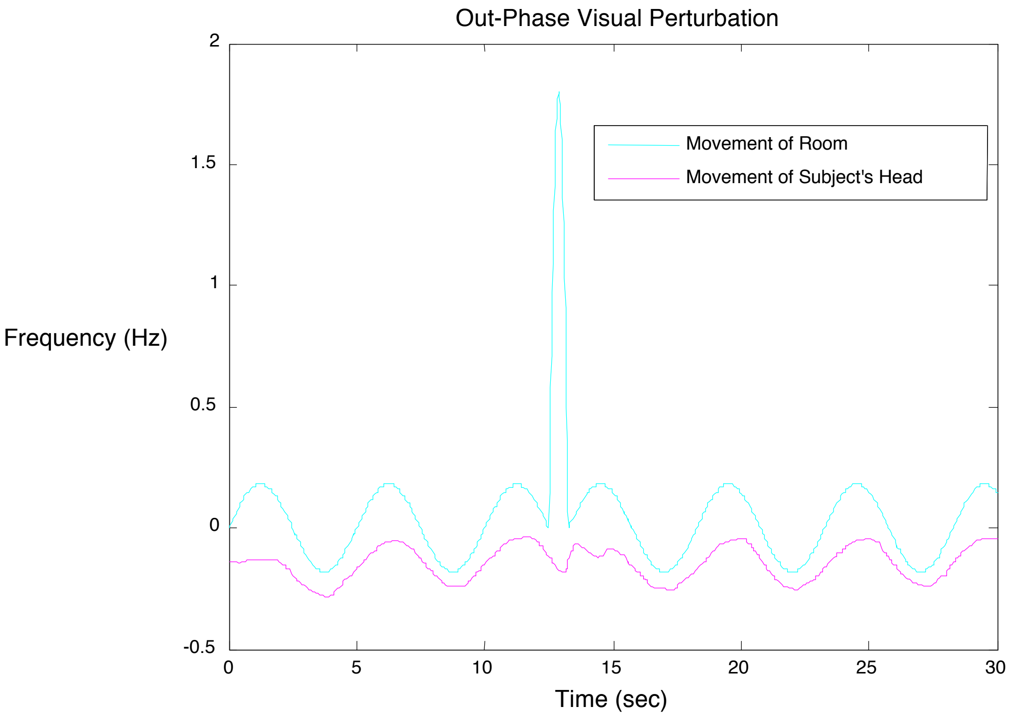

Figure 5: Pilot study displaying a pulse introduced out of phase to the movement of the room while the subject is in the Romberg stance

Figure 5 illustrates the movement of the room (blue) compared to the movement of the subject's head (magenta). An out of phase visual pulse interrupts the rhythm of the virtual room at 12.5 seconds, moving at 0.2 Hz. This figure depicts a moderate perturbation induced by the pulse while the subject is in a Romberg stance.

4. Establish a novel means of visual data analysis

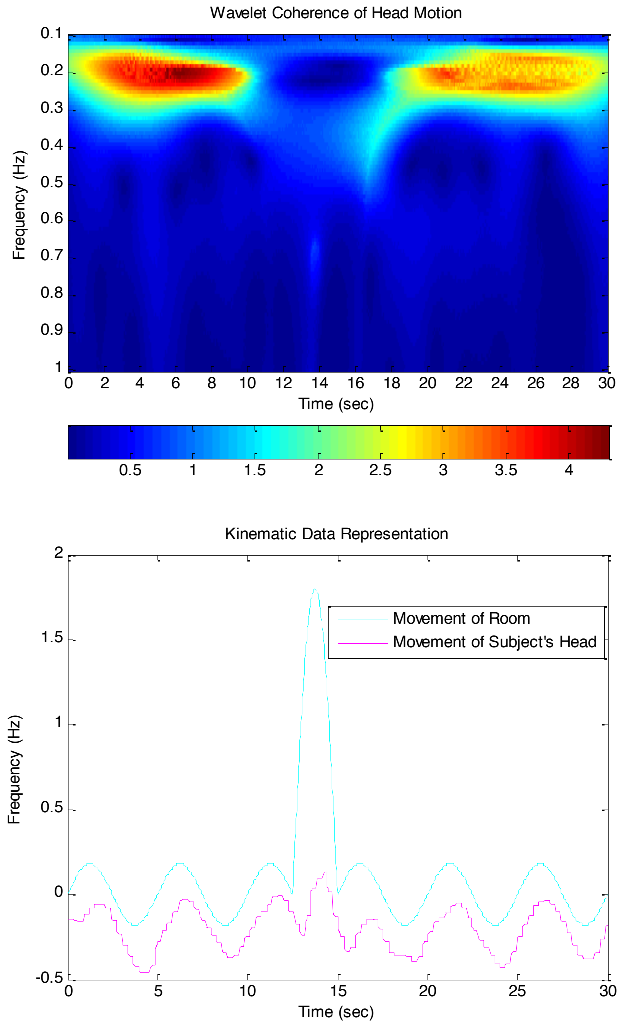

Figure 6: Wavelet (top) and kinematic (bottom) graphs depicting the coherence of a subject's movement in comparison to the movement of the virtual room

Figure 6 illustrates an example of the novel Wavelet visual analysis. The top figure corresponds to the bottom figure's data. A visual pulse of frequency 0.2 Hz is introduced at 12.5 seconds. The gap in coherence, representing the incoherence of the subject's movement to the movement of the room, is illustrated by the blue gap in Wavelet. The red color represents a coherence of movement in Wavelet.

5. Compare the effect of varying the frequency of a pulse on a patient's time to recovery of postural coherence

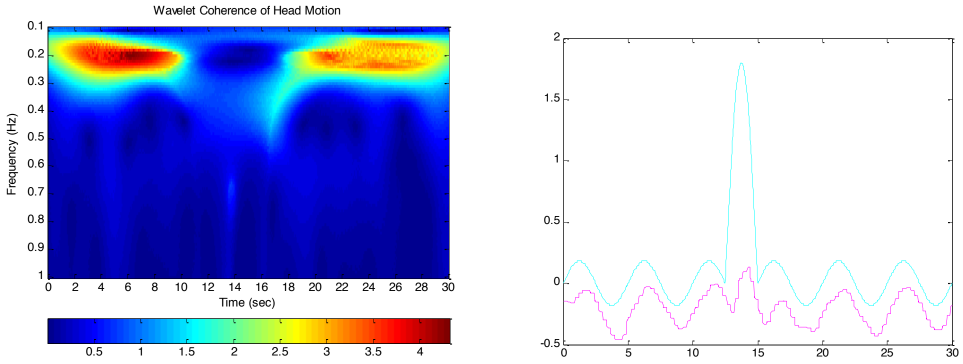

Figure 7: Unpredictable pulse of frequency 0.2 Hz shown by Wavelet analysis and kinematics

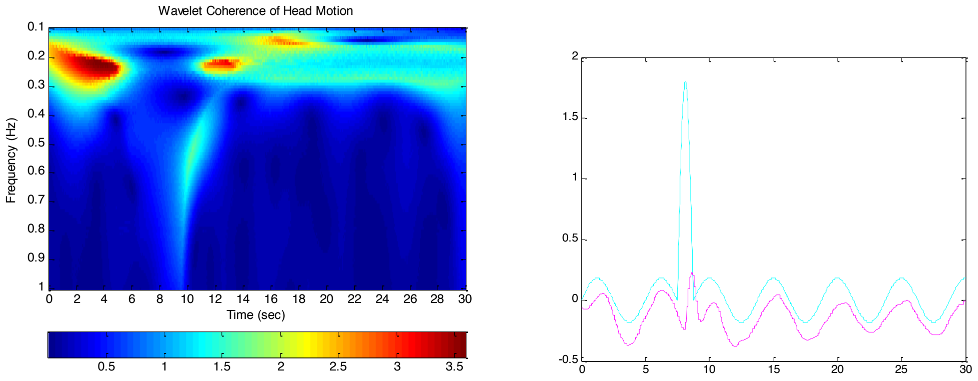

Figure 8: Unpredictable pulse of frequency 0.4 Hz shown by Wavelet analysis and kinematics

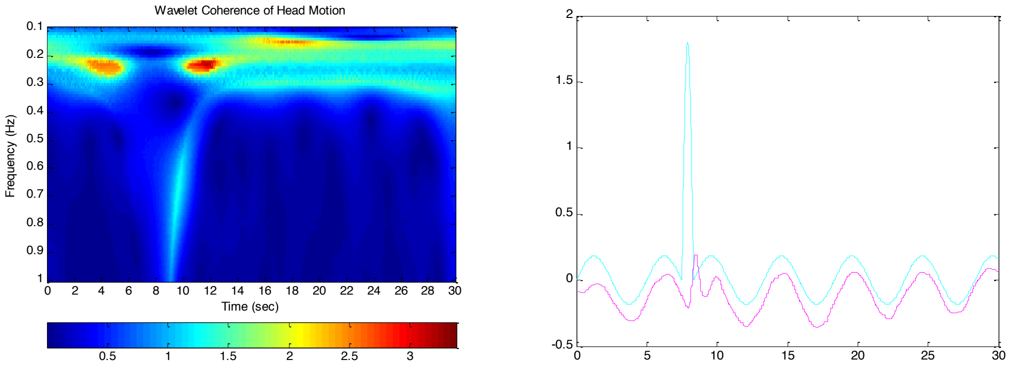

Figure 9: Unpredictable pulse of frequency 0.6 Hz shown by Wavelet analysis and kinematics

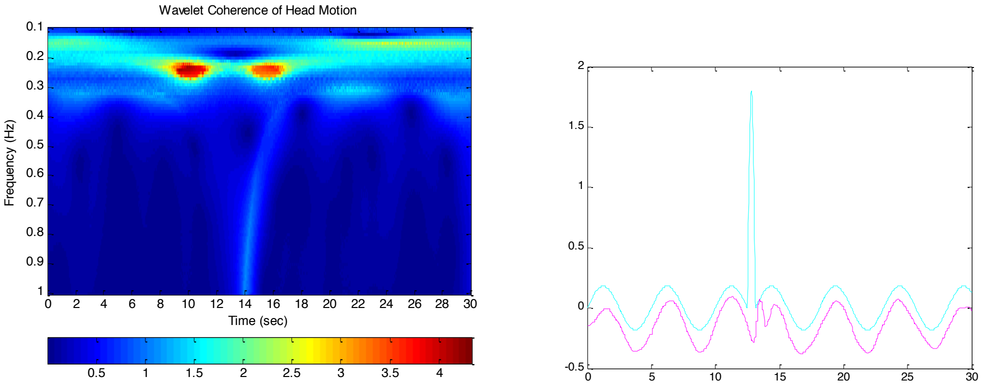

Figure 10: Unpredictable visual perturbation of frequency 0.8 Hz shown by Wavelet analysis and kinematics

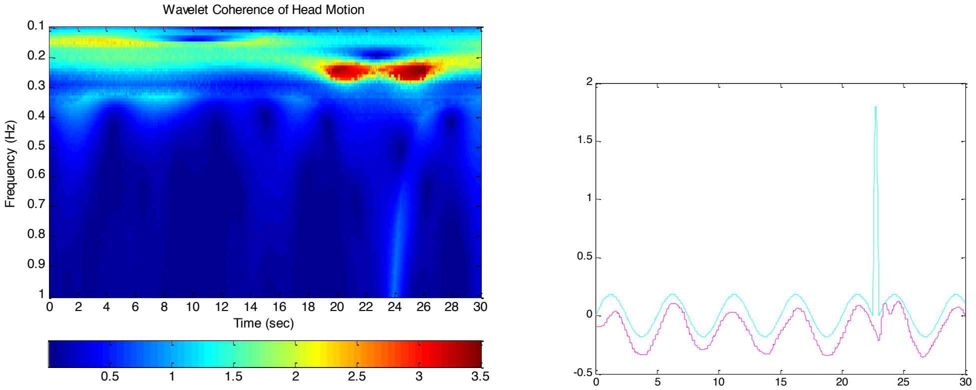

Figure 11: Unpredictable visual perturbation of frequency 1.0 Hz shown by Wavelet analysis and kinematics

The Wavelet and sinusoidal graphs in Figures 7-11 illustrate the effect of varying the frequency of a visual pulse introduced unpredictably to the continuously moving room. The gap in coherence, depicted by the blue gap in Wavelet, tends to decrease with the increase of frequency of the visual pulse.

6. Compare loss of balance due to unpredictable vs. predictable pulses

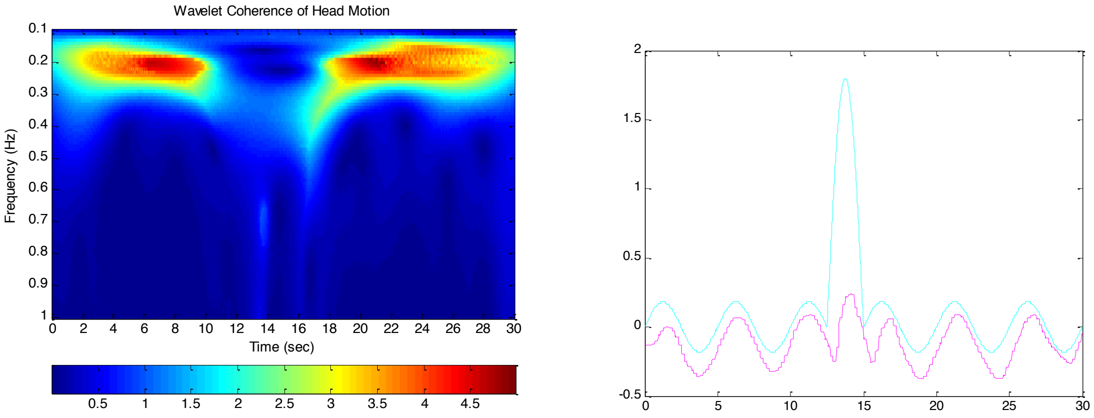

Figure 12: Predictable pulse of frequency 0.2 Hz shown by Wavelet analysis and kinematics

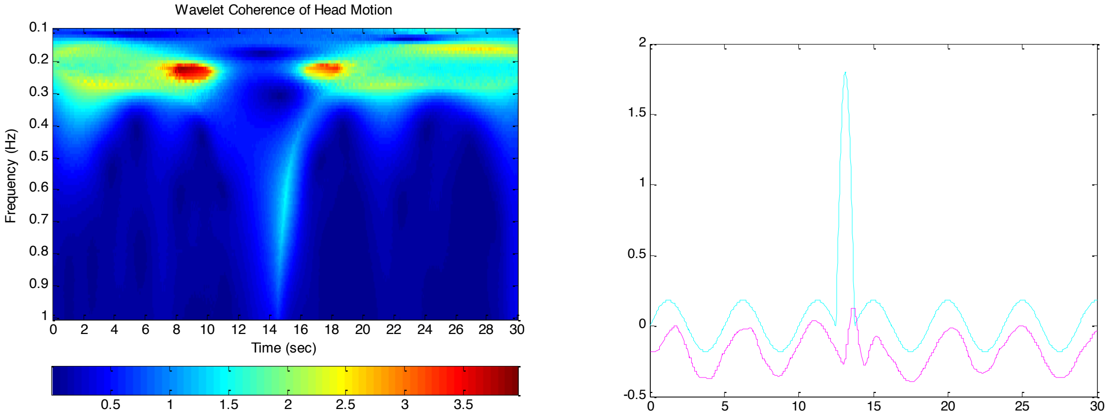

Figure 13: Predictable pulse of frequency 0.4 Hz shown by Wavelet analysis and kinematics

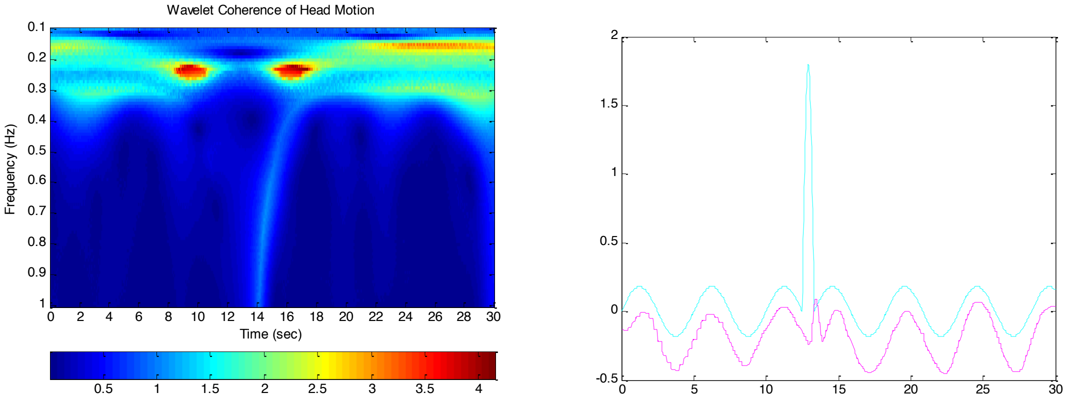

Figure 14: Predictable pulse of frequency 0.6 Hz shown by Wavelet analysis and kinematics

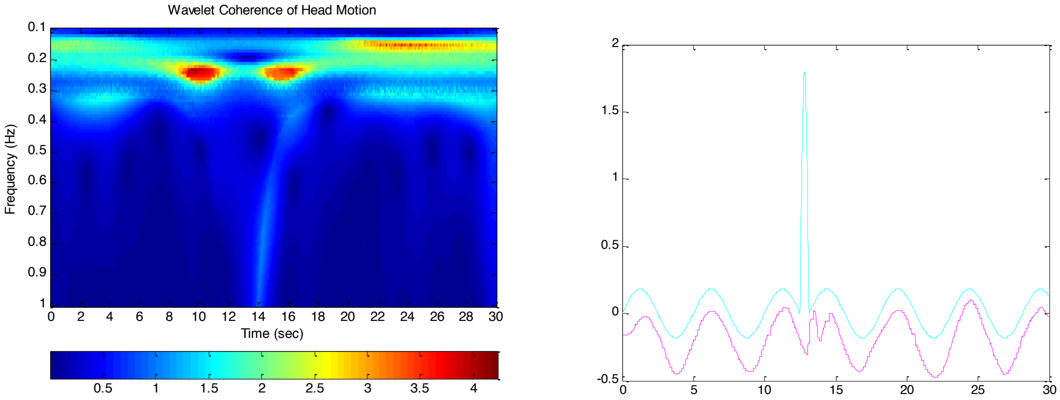

Figure 15: Predictable pulse of frequency 0.8 Hz shown by Wavelet analysis and kinematics

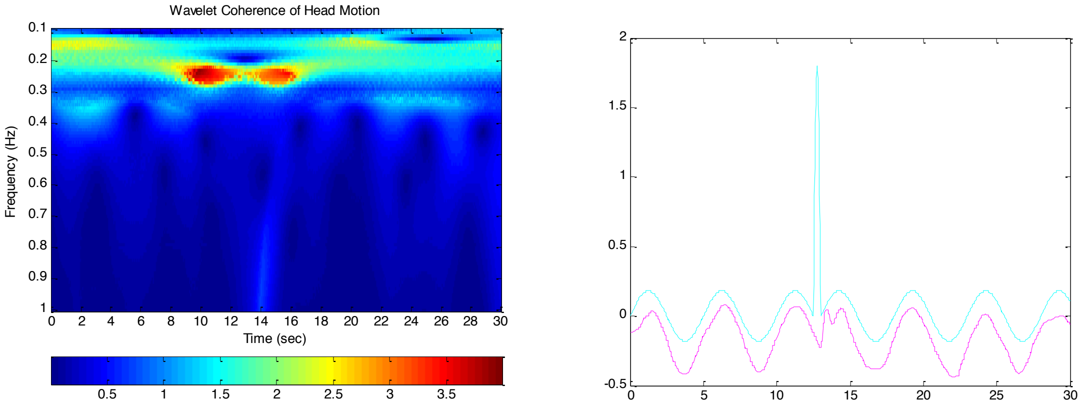

Figure 16: Predictable pulse of frequency 1.0 Hz shown by Wavelet analysis and kinematics

The Wavelet and sinusoidal graphs in Figures 12-16 illustrate the effect of varying the frequency of a visual pulse introduced predictably to the continuously moving room. The gap in coherence, depicted by the blue gap in Wavelet, tends to decrease with the increase of frequency of the visual pulse. This result is similar to the trend in the previous unpredictable condition.

Analysis

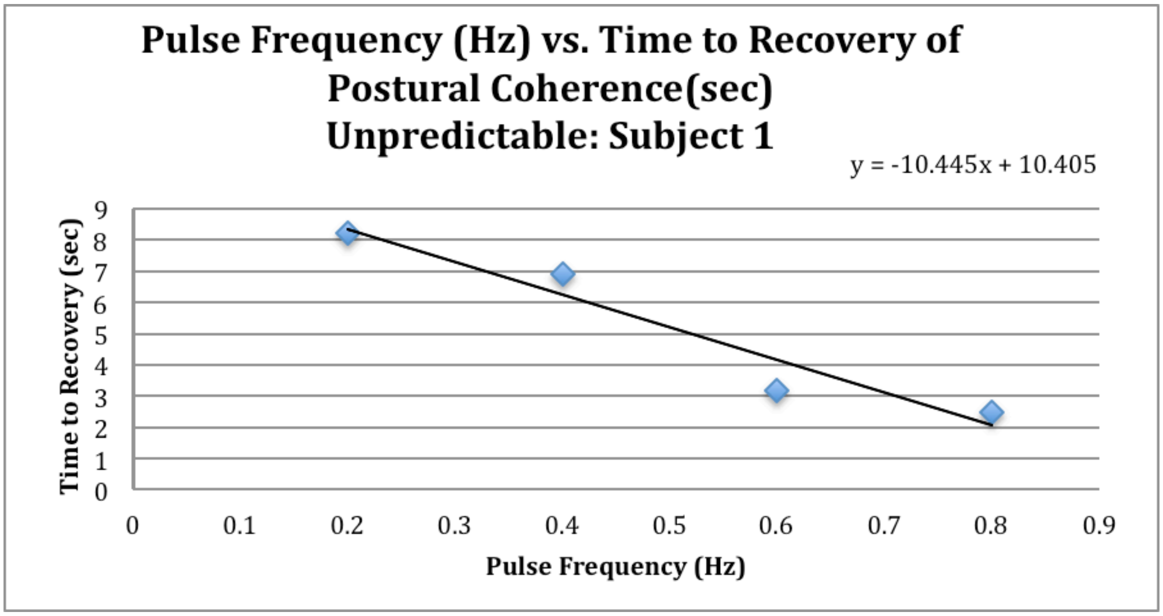

Figure 17: Linear regression displaying the average values for the time to recovery of postural coherence caused by the varying pulse frequencies of an out of phase pulse introduced in an unpredictable fashion to one subject

Pulse Frequency (Hz)	Time to Recovery of Postural Coherence (sec)
0.2	8.20
0.4	6.89
0.6	3.16
0.8	2.48

The linear regression illustrated by Figure 17 relates the frequency of the visual pulse (Hz) to the time to recovery of postural coherence (seconds) for Subject 1 in the unpredictable condition. The general trend follows a negative linear correlation. Increasing pulse frequency tends to decrease the amount of time to recovered coherence.

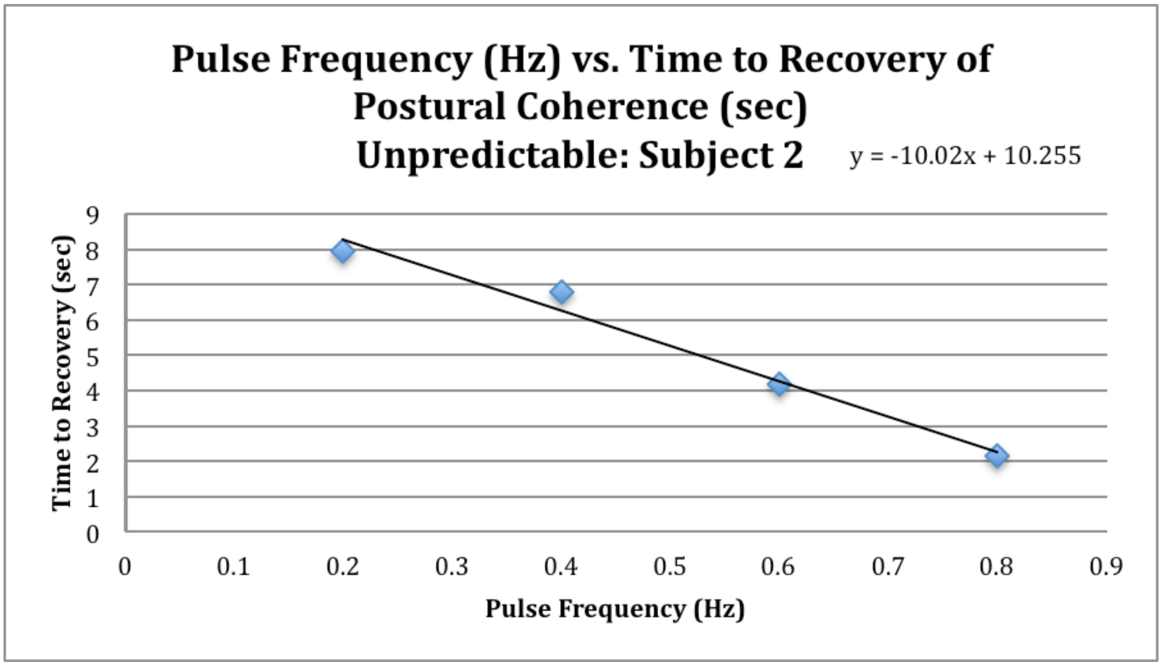

Figure 18: Linear regression displaying the average values for the time to recovery of postural coherence caused by the varying pulse frequencies of an out of phase pulse introduced in an unpredictable fashion to one subject

Pulse Frequency (Hz)	Time to Recovery of Postural Coherence (sec)
0.2	7.92
0.4	6.79
0.6	4.15
0.8	2.12

The linear regression illustrated by Figure 18 relates the frequency of the visual pulse (Hz) to the time to recovery of postural coherence (seconds) for Subject 2 in the unpredictable condition. The general trend follows a negative linear correlation. Increasing pulse frequency tends to decrease the amount of time to recovered coherence.

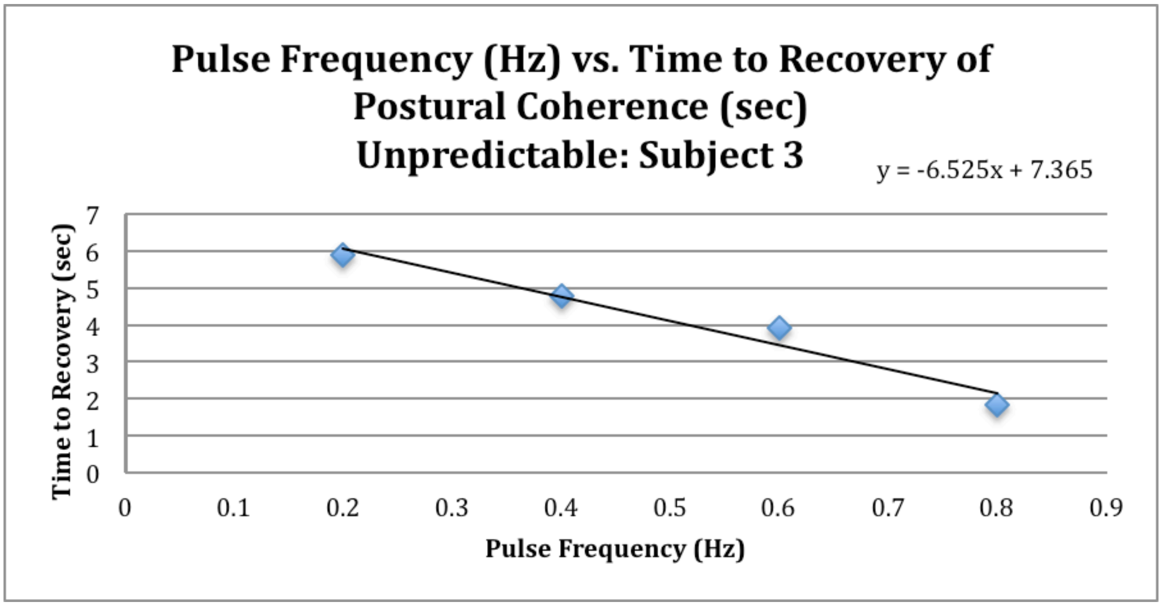

Figure 19: Linear regression displaying the average values for the time to recovery of postural coherence caused by the varying pulse frequencies of an out of phase pulse introduced in an unpredictable fashion to one subject

Pulse Frequency (Hz)	Time to Recovery of Postural Coherence (sec)
0.2	5.89
0.4	4.78
0.6	3.91
0.8	1.83

The linear regression illustrated by Figure 19 relates the frequency of the visual pulse (Hz) to the time to recovery of postural coherence (seconds) for Subject 3 in the unpredictable condition. The general trend follows a negative linear correlation. Increasing pulse frequency tends to decrease the amount of time to recovered coherence.

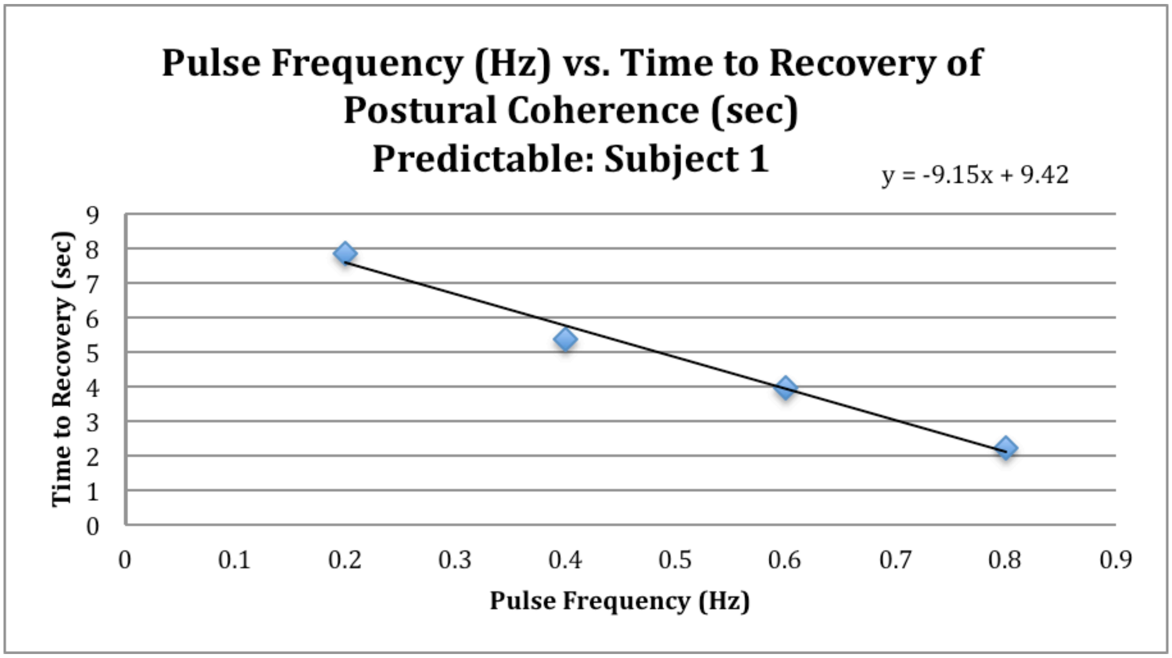

Figure 20: Linear regression displaying the average values for the time to recovery of postural coherence caused by the varying pulse frequencies of an out of phase pulse introduced in a predictable fashion to one subject

Pulse Frequency (Hz)	Time to Recovery of Postural Coherence (sec)
0.2	7.84
0.4	5.37
0.6	3.96
0.8	2.21

The linear regression illustrated by Figure 20 relates the frequency of the visual pulse (Hz) to the time to recovery of postural coherence (seconds) for Subject 1 in the predictable condition. The general trend follows a negative linear correlation. Increasing pulse frequency tends to decrease the amount of time to recovered coherence. The time to recovery values in this trial are somewhat lower compared to the same values for the same subject in the unpredictable condition.

Chapter 4

Discussion

Recent research has examined the temporal domain of assessing postural stability following a virtual pulse introduced to a continuously moving virtual room.[3] However, the predictability and the frequency of the pulse in relation to postural adaptation time due to optic flow is a novel topic of research. Considering that loss of balance in sport often occurs in dynamic and unpredictable situations, these factors are important to consider when developing clinical models to test an athlete's readiness for return to play.

A series of pilot studies were conducted in the preliminary protocol to determine: a benchmark amplitude and frequency to use for the pulse disrupting a 0.2Hz continually oscillating room, the foot stance of the subject while being tested (Romberg vs. bipedal), as well as the phase of the pulse (in phase vs. out of phase). Subjects responded well to a pulse with a frequency of 0.65 Hz and an amplitude of + 1.8 m. These parameters caused subjects to display an incoherence of movement when asked to match the cadence of the room's movement (see Figure 1.) The induced postural instability was of interest in asymptomatic baseline subjects to have a measurable time to recovery of postural coherence to compare between asymptomatic subjects as well as TBI patients in future protocols.

Subjects in the preliminary protocol were then introduced to this defined visual pulse while in two different stances: Romberg and bipedal. The pulse was introduced randomly within each 30-second trial. Figure 2 and 3 display the kinematic data displaying the differences in movement between the Romberg stance and the bipedal stance. For the Romberg stance, subjects were allowed to choose the most comfortable foot to be in front of the other. Subjects verbally proclaimed that the Romberg stance was more difficult to maintain. Also, a previous research study that looked at bases of support related to postural stability demonstrates how "subjects relied more on visual feedback to stabilize posture when standing on the most reduced base of support."[10] Although this particular finding was based off of studies investigating standing on one leg, the Romberg stance is thought to be more difficult to maintain stability in than the bipedal stance, yet less difficult than standing on one leg. With dynamic prolonged movements of this current study however, the probability of fatigue from standing on one leg lead to the use of the Romberg stance as a realistic conciliation.

The effect of the visual pulse being in phase or out of phase to the continuously moving room was also analyzed in the preliminary protocol. Previous research by Dijkstra, Schoner, Gielen had analyzed the effect of a visual perturbation that was "180 degrees…always at the point of maximum velocity (to avoid no discontinuity in position),"[5] and thus did not examine the effect of an out of phase pulse. The in phase pulse was introduced at 10 seconds when the room was moving in an anterior fashion. Since the defined pulse had a positive amplitude, this set-up allowed for an in phase effect. To produce an out of phase effect, the same pulse with a positive amplitude was introduced at 12.5 seconds, when the room was moving in a posterior direction, thus producing a change in direction (out of phase). Figures 4 and 5 illustrate the differences between these two conditions. It was professed that the out of phase condition produced postural incoherence that was slightly greater than that of the in phase condition. This effect, however, was not quantitatively investigated. This subjective result was not as pronounced as expected and perhaps future studies could analyze this phenomenon further. It was predicted that the out of phase perturbation would induce postural incoherence that was significantly greater than the in phase visual perturbation due to inertia. A mass in motion would be expected to resist any change in motion as described by Newton's first law. Thus, if a subject were to change direction of movement, it would be expected that the time to coherence of movement would be far greater than if the perturbed movement of the pulse occurred in the same direction of the movement of the room. This result was indeed perceived, however marginally and subjectively.

After conducting these pilot studies that analyzed how the foot stances and phase of the visual perturbation affected the postural stability of the subjects, these results were used to construct the specific protocol. The specific protocol utilized the findings of the preliminary protocol to incorporate into its protocol: using the pulse of amplitude +1.8 m while having subjects stand in the Romberg stance and introducing the pulse that was out of phase to the movement of the room. These conditions were shown to cause the most postural incoherence, which is of interest when trying to induce postural instability in asymptotic baseline subjects. The intention of the specific protocol was to test the affects of changing the frequency of the visual perturbation on time to stability, as defined as the time to recovered coherence of the subject to that of the room following the initiation of the pulse, as well as to see how the predictability of the pulse affected the time to stability.

Three subjects were tested in the specific protocol. These subjects were run through 30 total trials, each lasting 30 seconds; 15 of the trials were introduced randomly, the other 15 trials were introduced at a consistent time (at 12.5 seconds each time). All of the 30 trials manipulated the frequency of the pulse from 0.2 Hz- 1.0 Hz, with 3 trials per frequency. It is worthwhile to note that the order of the different frequencies introduced in the trials were reversed in the third subject to account for any learning effect that could have occurred.

Figures 7-16 display the results of these varying pulse frequencies by means of both kinematic data and of the novel Wavelet code display, which are discussed below. Previous pilot work had insinuated that pulse frequencies over 1.0 Hz could not produce meaningful responses from the subjects. Frequencies over 1.0 Hz were seemingly ignored by the subjects. Figures 11 and 16 display the effects of pulse frequencies of 1.0 Hz, where it is apparent that even this magnitude of a frequency makes it difficult to obtain an attempt at matched cadence by subjects and thus provides a very small gap between coherence and incoherence. For this reason, only frequencies of 0.2-0.8 Hz were used in regression analyses. This finding is an agreement with research by Dijkstra, Schoner, Gielen, who found that "spontaneous sway takes place in a frequency range below about 1.0 Hz."[5] Although this finding was related to continuous sway and not to abrupt visual perturbations, perhaps such postural trends are related. Likewise, Asten, Gielen, Denier van der Gon found similar results related to continuous sway: "the effect that the motion of the stimulus patterns has on postural balance, gradually decreases with the modulation frequency. Only for modulation frequencies below about 0.4 Hz are the magnitude of the normalized cross-correlational spectrum significantly affected by the visual input."[6] Asten, Gielen, Denier van der Gon go on to attribute this effect to biomechanical physiological properties where frequencies beyond normal postural sway could be "in conflict with information provided by other sensory systems…from the vestibular otoliths or muscle and joint receptors, overrules the information provided by the visual system…"[6] In other words, while the visual system may be the dominant mechanism in perceiving one's posture in relation to its environment, it is not the sole mechanism. Thus, if enough sensory information conflicts with the optic flow induced by the visual system, then the response may be ignored by the subject.

A novel means of visual data display and analysis was established to illustrate the coherence of movement in regards to the subject's movement and the movement of the room. Simple MATLAB plots have been used to graph the individual oscillation of both the room and the subject, however these are sometimes difficult to decipher the point at which postural coherence is reached. Wavelet, a novel MATLAB code, was designed to visually display coherence using a gradient of colors, where red depicts the highest coherence and blue depicts the lowest coherence. After introducing the visual perturbation to the subject, their coherence to the movement of the room is delayed due to optic flow. To measure the timing of this delay in seconds, the distance between the red coherences can be measured efficiently. To determine the exact value of the border of the red coherence areas, the median value on the Wavelet scale was used. After finding the matching color index value, the cursor was used to find the location of this precise color on the edges of the red portions by the blue incoherence gap, occurring during and immediately following the visual perturbation. The measurements used to calculate this gap were the values of these defined color borders produced by Wavelet. The pulse was thus included in the time interval of the incoherence gap.

After defining the location of the interval to be measured, these measurements were plotted in a regression analysis comparing the frequency of the pulse with the time to recovery (the value determined by the Wavelet incoherence gap). These plots are displayed in Figures 17-20. These graphs illustrate the primary finding that the 0.2 Hz pulse induces the longest recovery time and the 0.8 Hz induces the shortest recovery time. Since the lower frequency pulses are longer by nature, the question of whether this relationship would exist if measured from the end of the pulse to the point of coherence, instead of from the beginning of the pulse, was questioned. This relationship still existed with the mentioned consideration, however with a slightly less linear relationship, having the 0.2 Hz and 0.4 Hz pulse frequencies being more similar in recovery time, yet with the remaining frequencies beyond 0.4 Hz displaying the same shorter recovery times in a linear fashion. Nonetheless, the entire pulse itself was chosen to remain in the calculation of the graphed measurements because the pulse itself is inducing the postural response so it was decided that it was fitting to include the measurement of the pulse when analyzing time to recovery.

After determining this primary trend of decreased time of recovery to postural coherence with an increase in pulse frequency, the predictability of the pulse was analyzed. Between the two conditions of predictable vs. unpredictable pulses, it was determined that the unpredictable pulses required a slightly longer time to stability than those offered consistently as the same point in time. This relationship is depicted when comparing the values for Subject 1, depicted by the unpredictable condition in Figure 17 and the predictable condition in Figure 20. Both conditions show the same seemingly linear trend of increased time of recovery to coherence with a decrease in pulse frequency, yet the values for the unpredictable condition are slightly larger (8.20 sec, 6.89 sec, 3.16 sec, 2.48 sec) for three of the four frequencies when compared to the predictable condition (7.84 sec, 5.37 sec, 3.96 sec, 2.21 sec). There seems to be some variability in the time to postural coherence between subjects, yet the general trends of the effect of varying pulse frequency and predictability are similar. It is suggested to increase the number of participants in future investigation of this phenomena to strengthen the validity of the relationship and also to determine the scope of variability between subjects. This point leads to the potential importance of baseline testing individual athletes before they suffer a concussion to account for individual kinesthetic differences.

Wavelet has potential for clinical application for clinicians who want an efficient way to measure coherence of movement in virtual reality testing as a diagnostic tool for the treatment of concussed patients. The central idea being that concussed individuals theoretically would have a longer time to coherence, depicted by a larger blue gap on the Wavelet image. Further research is needed to investigate the relationship comparing the time to coherence between baseline and concussed subjects. Based on the findings of the specific protocol of this study, it is suggested that a pulse frequency of 0.2 Hz, or even 0.4 Hz, would induce the most dramatic postural incoherence effect when used with a 0.2 Hz continuously moving virtual room. Thus, the overall recommendation for clinical implications of this pulse protocol is to use a pulse frequency of 0.2 or 0.4 Hz introduced randomly and out of phase to a continuously moving virtual room, while in the Romberg stance.

In terms of a technical limitation, for pulse frequencies beyond 0.2 Hz, the red coherence areas of the Wavelet images do not pan across the entire trial. It would be expected that the coherence of the movement of the subject and the movement of the room would be coherent before the pulse and after recovery from the pulse. This is a scaling issue and an alteration to the Wavelet scaling could fix this concern for higher frequencies. Another consideration worth investigating is that the coherence gap sometimes begins before the pulse timing. For example, if the pulse was introduced at 10 seconds, the gap of coherence may begin at 8.5 seconds. This seems to be a consistent issue amongst trials and could potentially be resolved by choosing a lower color index to define the incoherence gap.

Beyond this technical obstacle, a general limitation of using virtual reality as a diagnostic tool is its potential for inducing motion sickness in some individuals. Tanahashi, Ujike, Kozawa et al. mention that "because motion sickness is often correlated with vection, based on our results it appears that conditions that readily cause motion sickness may also increase the occurrence of increased postural sway and falling," although this was not a problem during this set of pilot studies, it is a valid point that should be considered to readily circumvent potential problems as much as possible.[8] Also, individuals who have suffered ankle injuries or other impairments that reduce their ability to maintain normal postural control may not be able to benefit from this study's design and related virtual reality applications in balance testing.

The findings of this study as well as the development of a novel means of analysis, through Wavelet, have great potential for clinical application to supplement existing concussion testing protocols. Testing protocols that are sensitive enough to reveal subclinical residual effects of concussion injuries are valuable when ensuring athletes are indeed ready to return to play. The preliminary protocol of this study suggests that the use of an out of phase visual perturbation while in the Romberg stance in a virtual reality setting will produce the most optimal set of conditions for balance testing. The specific protocol investigated the effects of changing the frequency of a visual pulse. It was found that randomly introducing visual pulses of 0.2 or 0.4 Hz induce the longest time to recovery of postural coherence, while utilizing the conditions of the preliminary protocol. When constructing a clinical balance test using a visual pulse in a virtual reality setting it is thus suggested that the frequency used should be kept at 0.2 or 0.4 Hz to induce more dramatic incoherence of postural movement in baseline asymptomatic subjects to be able to optimally compare with concussed states. Future studies will investigate the comparison of time to recovery of postural coherence between baseline asymptomatic subjects and concussed subjects. Also, future studies could also look at the effect of different spatial movements of the subject. While this study looks at movement in the anterior-posterior direction, it would be interesting to see the effects of medial-lateral movements. Overall, this study worked to establish working protocols for more efficient visual perturbation-based concussion diagnosis.

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