Cardiovascular Responses to Vertical Whole-body Vibration

by

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Physiological Responses to Vertical Whole-body Vibration

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Abstract

The research done in this study investigates physiological responses to vertical whole-body vibration. The aim is to determine whether or not quantifiable responses can be found when evaluating changes in breathing rate, heart rate and heart rate variability. Such a relationship could potentially be used in vehicle dynamics industries to improve suspension system designs. This would be done by supplementing subjective testing techniques with a more objective physiological response when evaluating ride comfort.

A group of 60 volunteers were subjected to vertical whole-body vibration using a single seat actuator. The physiological parameters mentioned were measured during three different states, and the changes from state 1-2 and state 2-3 were recorded. The three states were each measured at different stages during the test procedure with stage 1 corresponding to the physiological state 1. Stage 1 consisted of baseline measurements, during this stage the test participant was not exposed to any vibrations at all. During stage 2 the participant was exposed to a reference vibration signal which is identical for all participants, and during stage 3 each participant was exposed to one of 4 alternative signals. The 4 alternative signals are all variants of the reference signal with increased amplitudes. The weighted amplitudes of each alternative signal were increased by 6.47%, 9.57%, 14.64%, and 20% respectively.

After evaluating the recorded data, it was found that the physiological change from state 1-2 was statistically significant for heart rate variability indicators. Unfortunately when evaluating the changes from state 2-3, there had been no statistically significant change. This suggests that while there is a clear and measurable physiological response to the initial vertical whole-body vibration, a change in this vibration is not reflected in the participant's physiological state.

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Nomenclature

Abbreviations:	
ANS:	Autonomic Nervous System
BPM:	Beats Per Minute
BR:	Breathing Rate
BMI:	Body Mass Index
ECG:	Electrocardiography
EEG:	Electroencephalography
EMG:	Electromyography
FFT:	Fast Fourier Transform
HF:	High Frequency
HR:	Heart Rate
HRV:	Heart Rate Variability
ISO:	International Organization for Standardization
LF:	Low Frequency
MTVV:	Maximum Transient Vibration Value
Nfft:	Number of Fast-Fourier Transfer points
NN50:	RR intervals that differ by more than 50ms
PSD:	Power Spectral Density
pNN50:	RMS of the sum of successive RR intervals delta
RMS:	Root Mean Squared
RMSSD:	Root Mean Squared Standard Deviation
RR:	R-R interval, interval between two heartbeats
SD:	Standard Deviation
SOP:	Standard Operating Procedure
WBV:	Whole Body Vibration
VDV:	Vibration Dose Value
Symbols:	
A	Amplitude
F	Frequency Domain Signal
fs	Sample Frequency
$\emptyset$	Phase angle
$\boldsymbol{n}$	Number of Participants
$\boldsymbol{Z_{\alpha}}$	Significance Constant (P-value)
$\boldsymbol{Z_{1-\beta}}$	Confidence Interval Constant
Δ	Expected change
$\boldsymbol{\sigma}$	SD
$\boldsymbol{K_z}$	Z-Axis Constant
$\boldsymbol{K_y}$	Y-Axis Constant
$\boldsymbol{K_x}$	X-Axis Constant

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Chapter 1: Introduction

Vehicle dynamics is an expansive field that constantly evolves with new advancements in technology. These advancements provide vehicles with improved safety, comfort, reliability and performance. This study is related to the advancements in ride comfort, and when evaluating ride comfort specifically, there are well documented and universally recognised methods and procedures.

Over time the methods by which ride comfort is measured and evaluated have become standardised in documents such as ISO 2631 and BS 6841. As demonstrated multiple times by several research papers such as (Zhou and Griffin, 2014) and (Els, 2005), the techniques for measuring and evaluating ride comfort in these documents correlate very well to the subjective observations of vehicle occupants. This research explores the possibility of supplementing ride comfort evaluations with objective physiological measurements that could potentially mitigate subjective-objective variations caused by varying human physiology.

1.1 Dissertation Overview

This document is split into seven chapters, each discussed here. Chapter 1 serves as an introduction to the document, and contains this overview. This chapter is intended to assist the reader by providing a breakdown of the document and what each section entails. Chapter 2 focuses on literature that has been studied during the course of this dissertation. The chapter begins by exploring how whole-body vibration is measured and evaluated. Following this, the physiological effects of vibration are explored. The researcher then demonstrates how to evaluate physiological parameters, and the significance of statistical evaluation is highlighted. The chapter ends with a summary of relevant previously completed research, from which the research question is properly formulated.

In Chapter 3 of this dissertation the safety requirements and precautions taken are explained. The chapter also includes the selection criteria for all volunteers, as well as a summary of the physiological parameters for the volunteers as a group. The experimental procedure for the pilot study is documented in Chapter 4. The chapter includes details about the equipment as well as the data processing methods used. This chapter is split, and also includes the results and discussions from the pilot study.

Chapter 5 documents the experimental procedure for the main study and follows a similar process to Chapter 4. Experimental results are presented as a set of figures with tabulated data. Chapter 6 is the final chapter and includes the conclusions of this dissertation and recommendations for future work. Figure 1 provides a graphical overview of the dissertation, with a short summary of what is covered in each chapter.

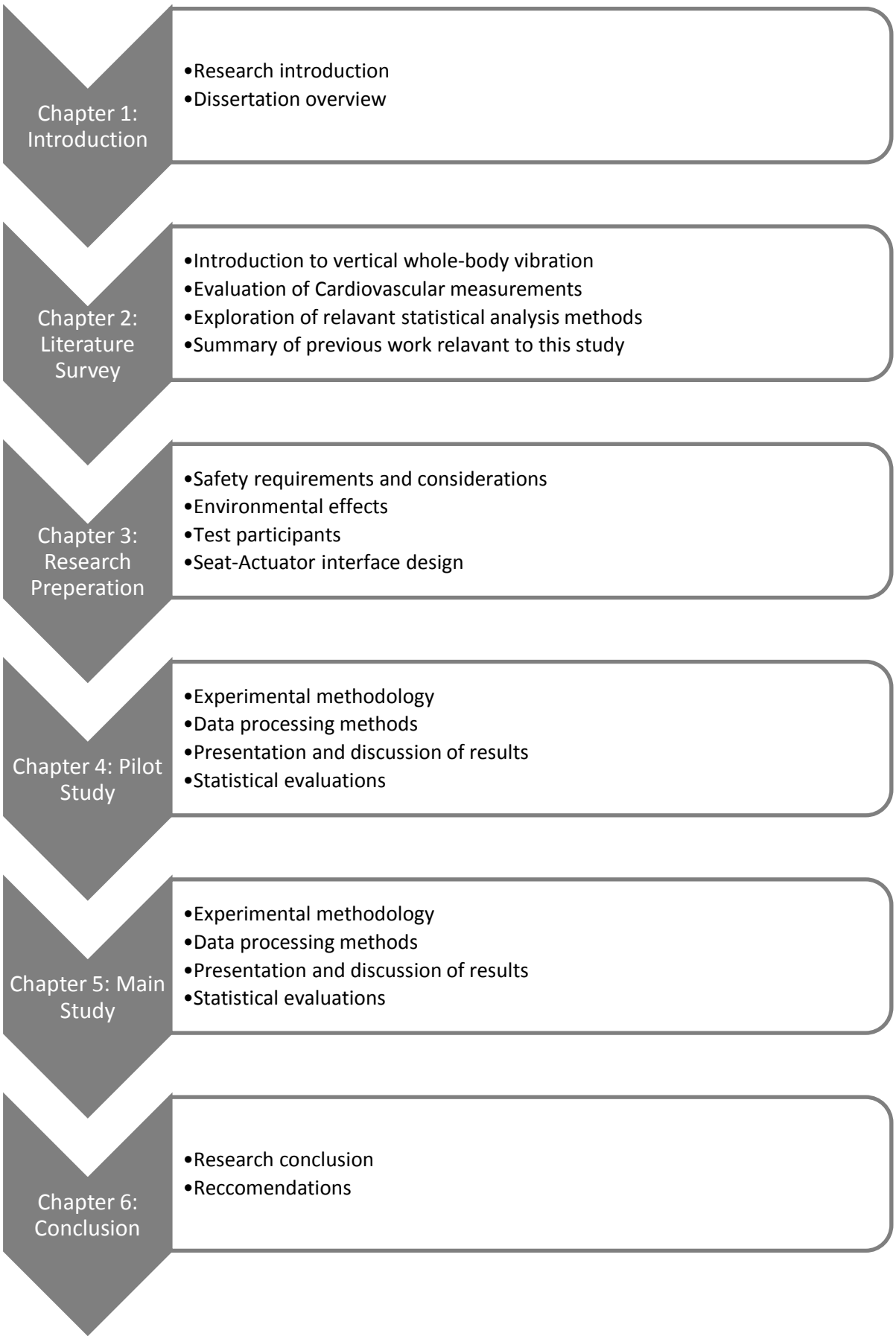

Figure 1: Dissertation Overview

Chapter 2: Literature Survey

The literature survey in this dissertation serves to summarise and present research that is relevant to this study. Section 2.1 focuses on whole-body vibration and ride comfort, showing how it is measured and evaluated. Section 2.2 evaluates the effects of whole-body vibration on the human body and from this the physiological parameters to be measured are identified. Section 2.2.6 focuses on the statistical analysis of physiological measurements in previous studies. Section 2.4 closes the literature survey with a summary of findings from similar research and a literature survey conclusion. From this, the research question is formed.

2.1 Ride Comfort Evaluation

This section of the dissertation focuses on how ride comfort is evaluated. It documents the standard methods and equipment used when determining ride comfort, and explores subjective vs objective evaluations. Although there are many factors that can influence ride the perceived ride comfort of a vehicle occupant, ISO 2631-1 (ISO, 1997) recognises vibration as a significantly contributing factor.

2.1.1 WBV in Ride Comfort

As the name suggests whole-body vibration (WBV) refers to vibration which affects the whole body, this is different to local vibration which affects just a specific body part. The handbook of human vibration (Griffin, 2012) states that whole-body and local vibration are not exclusive and that both types cause vibration throughout the body. The two are distinguished by local vibration being present when vibration is applied to one or more limbs, and whole-body vibration being applied when the body is supported by a vibrating surface.

The vibrations present in vehicles are very complex, consisting of multiple sources of vibration in several different directions. In addition to variations in direction, there are significant variations in both the amplitude and frequency of WBV in vehicles. ISO 2631-1 (ISO, 1997) documents the process used to evaluate ride comfort using WBV. The handbook of human vibration (Griffin, 2012) and the standard (ISO, 1997) both demonstrate that the human body is more sensitive to some vibration frequencies than others. The handbook also identifies frequency, magnitude and duration of vibration to directly affect perceived ride comfort. Studies performed on WBV such as (Nishiyama et al., 2000, Wang et al., 2006) and (Nawayseh and Griffin, 2010) show that posture and seat positioning affect perceived ride comfort. Research done by (Toward and Griffin, 2011) also demonstrates that the physical characteristics of the occupant has an effect on perceived ride comfort.

Most, if not all, studies involving human participants have small discrepancies in the recorded data between that is attributed to inter-personal variability in biodynamics. While this does not affect all research, (Zhou and Griffin, 2014) is an example of such a research paper. The handbook of human vibration (Griffin, 2012) also explicitly lists the physiological and psychological state of a test participant as confounding factors along with posture, position and the interaction between the body and the vibration source.

The research done by (Nawayseh and Griffin, 2010) and (Toward and Griffin, 2011) show that human physiology has an effect on perceived ride comfort. Variations in weight, size and posture in humans cause differences in the vibrations applied to each individual body. The differences in biodynamics have been described using mechanical impedance and apparent mass, transmissibility changes and vibration power absorption. The paper by (Nawayseh and Griffin, 2010) favours vibration power absorption, in which the body can be seen as a damper. This damping coefficient would be different for each individual, and change with posture and position.

Knowing that human physiology affects vibration transmissibility suggests that ride comfort evaluations will benefit from physiological measurements. There is a disconnection between the vibration applied by the source and the vibration felt by the participant. Research often highlights inter-person variability (biodynamic variability) as the cause for inconsistent data, and evaluating ride comfort by measuring physiological changes may overcome this obstacle.

2.1.2 Testing Platform

This section of the dissertation serves to address how the test participants will be exposed to WBV. Table 1 summarises the equipment used in previous work that has been studied to serve as examples of how this is typically done.

Table 1: Summary of Equipment Used to Apply WBV to Test Participants

Paper:	Equipment:
(Zhou and Griffin, 2014)	Seat bolted to vibrating platform
(Toward and Griffin, 2011)	Seat bolted to vibrating platform
(Wang et al., 2006)	Seat bolted to vibrating platform
(Els, 2005)	Field tests with military vehicle driven over rough terrain
(Nishiyama et al., 2000)	Seat with pedals and steering wheel bolted to vibrating platform
(Wikström et al., 1991)	Field tests with two separate vehicles driven on different terrain
(Howarth and Griffin, 1991)	Seat bolted to vibrating platform
(Paddan and Griffin, 2002)	Field tests with multiple vehicles on multiple different terrains
(Nawayseh and Griffin, 2010)	Seat bolted to vibrating platform

Although more than half of the papers listed involve the same researcher, a vibrating platform with various attachments such as a seat has been found to be the ideal testing apparatus. Field tests with vehicles are the most realistic tests possible, but in cases where repeatability is required the driver would need to traverse the same portion of track at the same speed. The lab based platform allows complete repeatability and environmental control.

Other testing apparatus such as the 4-poster lab based apparatus could certainly be used to apply WBV to a test participant, but the equipment is expensive and is designed for the evaluation of suspension systems rather than WBV. According to the literature covered, it is recommended that the experiment makes use of a vibrating platform. When selecting a seat to mount to the vibrating platform (Nawayseh and Griffin, 2010) demonstrates that the presence of a footrest would reduce vibration power absorption. Incorporating a backrest will reduce power absorption at low frequencies, but increase it at higher frequencies.

Research done by (Paddan et al., 2012) shows that perceived ride comfort decreases with larger back rest angles, suggesting that more upright positions are more comfortable. Work done by (Toward and Griffin, 2011) suggest that contact with any backrest at all reduces comfort since the backrest acts as another source of vibration. In order to reduce biodynamic variability the testing platform used should incorporate a footrest. When considering incorporating a backrest it is clear that incorporation of a backrest would offer more safety to participants. The vibrations present on at the backrest should not be ignored, and should be compared between participants.

2.1.3 Objective Measurement Techniques

This section documents the process outlined in ISO 2631-1 for evaluating ride comfort from WBV. Before this is done, the reasons for using ISO 2631-1 rather than other standards must be addressed. A study done by (Paddan and Griffin, 2002) evaluated the differences between the ISO (ISO, 1997) and BS (BS, 1999) standards for ride comfort evaluation.

The two main differences between the two standards are that for safety evaluations BS 6841 considers an equivalent acceleration and ISO 2631 simply considers the largest vibration. The BS standard also has a 4 axis system where the ISO standard only uses 3. (Paddan and Griffin, 2002) concluded that the BS standard is much stricter on allowable vibrations than the ISO version, and that in some cases the ISO version may underestimate the vibration severity. The ISO standard was used in this study because the experiment is only concerned with vertical WBV which is the dominant vibration found in normal passenger vehicle operation.

According to ISO 2631-1 (ISO, 1997) there are several vibration evaluation methods for ride comfort, the first of which is to calculate the weighted root mean squared (RMS) acceleration for the given vibration signal. The accelerations are frequency weighted according to Figure 2 in order to compensate for humans being more sensitive to certain frequencies. This method is not applicable if the vibration crest factor exceeds 9, or if occasional shocks and transient vibration is present. A vibration signals crest factor is calculated as the ratio of the maximum weighted acceleration value to the weighted RMS value.

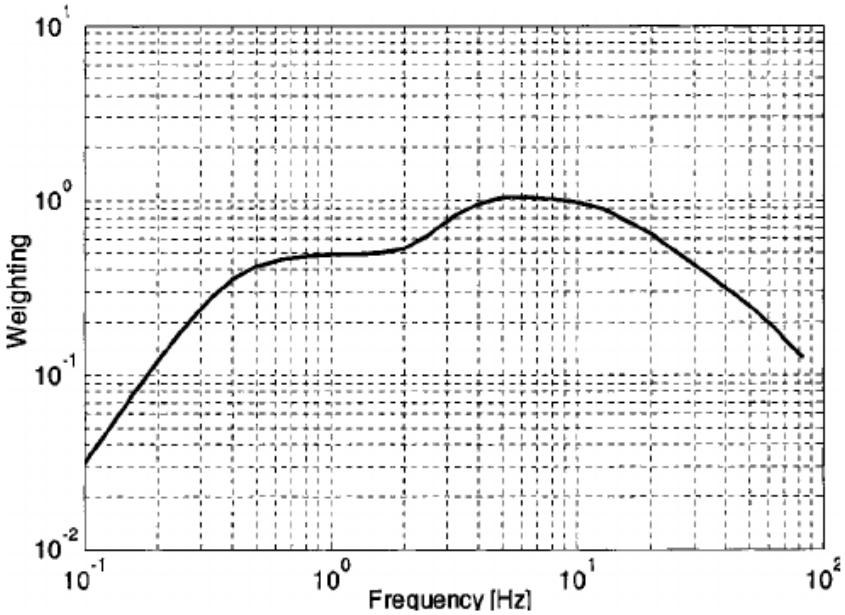

Figure 2: Wk Frequency Weighting Curve (ISO, 1997, Reynolds, 2003)

In cases where occasional shock and transient vibration are present, the running RMS method may be used. This method makes use of a short integration time constant, and the vibration magnitude is defined as the maximum transient vibration value (MTVV). The final method described is the vibration dose value (VDV) calculation which is applicable for high crest factors as well as standard calculations. Once the vibration magnitude has been calculated, it can now be evaluated with regards to comfort and health. The health guidance in ISO 2631-1 is only applicable in the 0.5 to 80Hz frequency range. The health and safety requirements for vibration experiments are covered in Section 2.1.5 of the dissertation. Table 2 gives a summary of ride classifications based on weighted RMS acceleration values which serves as a guideline for evaluating ride comfort.

Table 2: Weighted RMS and Perceived Comfort (ISO, 1997)

Weighted RMS Acceleration [m/s^2]:	Perceived Comfort:
Less than 0.315	Not Uncomfortable
0.315 – 0.63	A Little Uncomfortable
0.5 – 1	Fairly Uncomfortable
0.8 – 1.6	Uncomfortable
1.25 – 2.5	Very Uncomfortable
Greater than 2	Extremely Uncomfortable

2.1.4 Subjective Measurement Techniques

The previous section dealt with objective ride comfort measurements which can be done without any subjective input from the test participant. This section focuses on subjective ride comfort evaluation. It is worth noting that the objective measurements have been thoroughly investigated and can be used with confidence, work done by (Els, 2005) is just one of many studies that confirm correlations between subjective and objective measurements.

Subjective evaluations are typically performed by subjecting a test participant to one or more vibration signals and then asking the participant a series of questions. The questions are often presented in the form of a questionnaire. The questionnaire typically includes some questions on perceived comfort as well as some physiological parameters.

2.1.5 Vibration and Health

As with any research, the ensured health and safety of any participant is a priority. The safety requirements for any experiment that exposes test participants to vibrations is documented in ISO 13090-1 (ISO, 1998). The standard sets these requirements for several aspects of the experiment including the vibrations participants are exposed to, the procedure followed and the people present during the experiment. Before any tests can be conducted at the university clearance is required from the ethics committee, the committee ensures that all safety requirements have been met. The clearance from the Engineering, Built Environment and IT (EBIT) and the Health Sciences Research Ethics faculty committee of the University of Pretoria are in Appendix A of this document.

The hazards inherent to mechanical vibration can be separated into three main groups (ISO, 1998). The first is exposure to vibration, exposure to vibration and repeated shock may lead to injury. The second group deals with the system used to expose participants to vibration, and the third group sets requirements for personnel and staff.

The standard has several requirements for each group which is summarized in Table 3. Wherever the table refers to RMS values, these values are the frequency weighted RMS values for acceleration measured during vibration. The vibration exposure requirements are shown in Figure 3, where equation A.2 is more conservative for shorter durations. The figure shows a set of two lines for each equation, any severity below the bottom line is considered safe, and any above the upper line is considered unsafe. The area between the two is a risk area and requires a physician to be present.

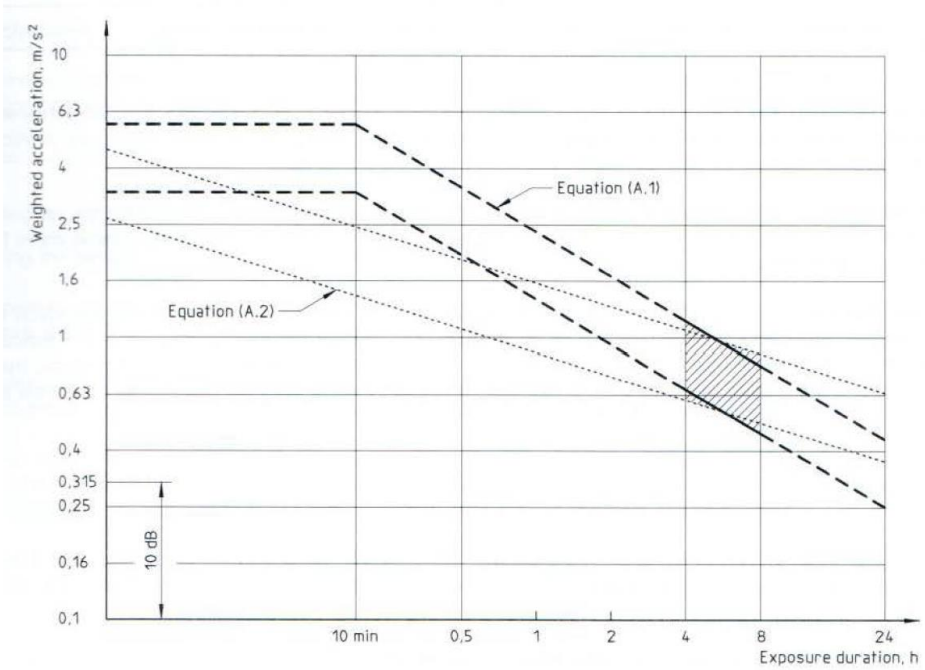

Figure 3: Weighted RMS vs Exposure Duration for Safety (ISO, 1998)

Table 3: Summary of ISO 13090-1 Safety Requirements

Vibration Exposure Requirements	
Exposure duration and severity	Vibration exposure of 16min may not exceed 2.2 m/s^2 RMS Vibration exposure of 5min may not exceed 3.5 m/s^2 RMS
Exposure system during failure	VDV for entire signal may not exceed 17$m/s^{1.75}$ One second RMS over peak acceleration may not exceed 10m/s^2
System Requirements	
Relative motion	Surrounding staff and equipment must be clear of vibrating platform Test participant must be secured to prevent falling
System failure	System must be protected from mechanical, electrical and software failure, not exceeding vibration limits in case of failure
Record keeping	A comprehensive record of tests performed with observations must be kept for revision in case of an accident
Personnel Requirements	
Physician or doctor	If the vibration severity exceeds the safe threshold then a physician or doctor must be present during testing
Experimenter and operator	The experimenter is the person taking responsibility for the experiment, and may also be the operator operating the equipment
Operator	The operator of the test equipment must be familiar with the emergency procedures.
Observer	If the operator does not have a clear view of the test participant and equipment an observer is necessary

2.2 Physiological Measurements

At the end of the introduction in Chapter 1 of this dissertation, the use of physiological measurements in WBV evaluation is proposed. In Section 2.1.1 the researcher proposed that making use of these measurements may mitigate the effects of physiological differences on ride comfort evaluations. This section of the literature survey explores this proposal by evaluating the effects that WBV has on human physiology.

2.2.1 The Autonomic Nervous System (ANS)

Before any meaningful conclusions can be drawn from studying previous research, it is important to understand the mechanism which controls physiological reactions. The autonomic nervous system (ANS) is the part of the nervous system responsible for most visceral (passive) functions of the body. As stated by the textbook of medical physiology (Hall.J, 2006) this includes the regulation of blood pressure, body temperature, and sweating. (Hall.J, 2006) demonstrates how rapidly the ANS can respond to an external stimulus on the body by stating that it is possible for the ANS to double heart rate within 3 seconds should the need arise. The ANS adjusts and controls all physiological parameters within the human body, which must change in response to an event or external influence in order to maintain homeostasis.

(Cannon, 1939) and (Ramsay and Woods, 2014) define homeostasis as the continuous regulation of vital physiological variables, and is the core concept of physiological regulation. Their research demonstrates that the ANS plays an essential role in balancing temperature, blood sugar, and oxygen in the blood as well as controlling the actions of internal organs in order to maintain homeostasis.

In order to maintain homeostasis the ANS is divided into two main parts referred to as the parasympathetic and the sympathetic branches and by working together they maintain homeostasis. The parasympathetic branch is responsible for a resting state, controlling the body processes during ordinary situations. (Cannon, 1939) and (Hall.J, 2006) refer to this as the “rest and digest” functions. This means that in general parasympathetic reactions reduce blood pressure, slow heart rate, stimulate the digestive tract to process food and use energy to restore and build tissue. (Hall.J, 2006) and (Lou.P, 2018) demonstrate that the sympathetic branch is responsible for “Fight or Flight” reactions during stressful situations. A sympathetic response increases heart rate and the force of cardiac contractions, increasing muscle strength and causes the body to release stored energy. Table 4 summarises the specific effects that the two branches have on various organs.

Table 4: Autonomic Nervous System Effects (Hall.J, 2006, Lou.P, 2018)

	Sympathetic	Parasympathetic
Eye	Pupil dilation	Pupil constriction
Sweat Glands	Copious sweating	-
Heart	Increased rate and force of contraction	Slowed rate and force of contraction
Lungs	Dilation of bronchi	Constriction of bronchi
Liver	Stimulates glucose production	Restoration and cell growth
Stomach	Inhibits digestion	Stimulates digestion
Gall bladder	Inhibits secretion	Stimulates bile release
Mental Activity	Increased activity	Restoration and cell growth
Skeletal Muscles	Increased strength	Restoration and cell growth

2.2.2 Physiological effects of WBV

WBV has been studied extensively by both mechanical and medical faculties in different ways. Section 2.1.1 focused on the perceived ride comfort as a result of WBV, in this section physiological responses to WBV are evaluated. WBV is an external stimulus that will force the ANS to react in order to maintain homeostasis.

When WBV is considered as physiological stress for the body, it becomes easy to predict the effects it would have on various organs. As described by (Lou.P, 2018) the heart will react to physiological stress by increasing heart rate (HR) and reducing heart rate variability (HRV). Similarly, physiological stress will also increase breathing rate (BR). According to (Hall.J, 2006) the ANS will also cause pupil dilation, sweating as well as increased muscle and brain activity. With this in mind, the researcher will make use of BR and HR during physiological measurements.

2.2.3 Physiological Response Measurement

There is electrical activity associated with the movement of every muscle in the human body. This impulse is conducted throughout the body through various tissues and eventually reaches the surface of the body where it can be measured with electrodes on the skin. The measurement and recording of this electrical activity is called electrography.

(Hall.J, 2006) shows that while all electrical pulses in the body originate from the nervous system, there are three different types of electrography. These are Electrocardiography (ECG – Measuring the heart), Electroencephalography (EEG – Measuring the brain) and Electromyography (EMG – Measuring muscle tissue). Ideally the equipment to be used when evaluating physiological responses would incorporate all three electrograms. The only one of these readily available at the University of Pretoria is the ECG apparatus.

2.2.4 Electrocardiography (ECG)

An electrocardiogram, also known as an ECG or EKG, is the measurement and recording of the electrical activity of the heart through a series of sensors placed in specific places on the body. The sensors used typically consist of 10 adhesive electrodes for a 12 lead ECG as used by (Plotnick and Lemkin, 2016), and 3 electrodes for a 3 lead ECG. Each “Lead” refers to the heart’s electrical activity along a particular vector (A direction) in three dimensional space. This occurs as a result of measuring electric potential between two electrodes, which would naturally have a direction of flow between them. As a result the placement of these electrodes is very important, (Hall.J, 2006) demonstrates that the 10 electrodes used for a 12 lead ECG consist of 4 limb electrodes placed on wrists and ankles and 6 precordial electrodes placed on the chest.

(Schnell et al., 2013) and (Dijksterhuis et al., 2011) show that performing an ECG, it is possible to determine the subject’s heart rate, which often referred to as the pulse. This is measured as the average beats per minute (BPM). The normal resting HR for an average adult is between 60 and 100 BPM. Although BPM is measured, it is important to note that the beats do not occur at regular intervals. This variation in beat intervals is called heart rate variability (HRV). HRV, or R-R variability, is a much more useful physiological measurement than HR alone. It is defined in (Hall.J, 2006) as the variation between the QRS R to R peak interval lengths on a standard ECG trace. R-R intervals are typically plotted as a time series called a tachogram, and from this several evaluations can be performed (Hall.J, 2006, Guger, 2004).

ECG equipment usually displays a graph called an ECG trace. This trace is a wave-form representation of the patient's heartbeat and has repeated sequences of waves called QRS complexes. A standard QRS complex is shown in Figure 4, and is so named because of the distinct features of the wave labelled Q, R and S. A qualified medical doctor can tell a lot about a patient's heart and general health by carefully evaluating the shape and magnitude of the QRS complex, but for this research only the R peak is relevant. An action potential is simply a very small electrical impulse that travels along the nervous system and causes the heart muscles to contract. The QRS complex that appears on an ECG trace is a representation of action potentials in the heart which cause it to beat (Bohan, 2005).

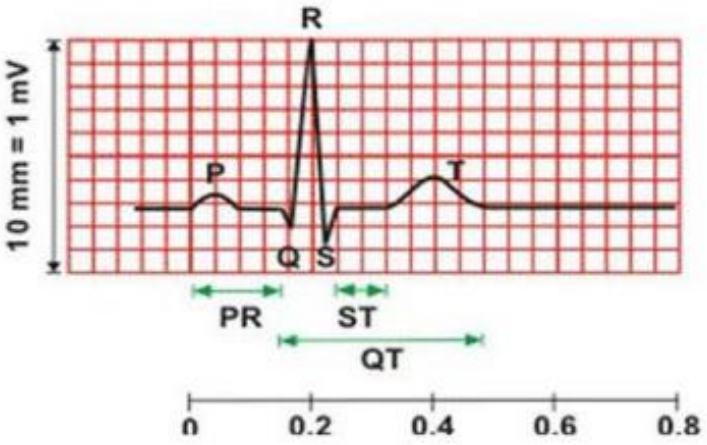

Figure 4: Standard QRS Complex (Stephens, 2014)

2.2.5 Evaluation of HRV

There are several different indicators that are used when determining HRV and all of these indicators are listed in Table 5. (Malik, 1996) demonstrates that when the body is subjected to physiological stress, HRV indicators correspond to the ANS sympathetic reaction. (Malik, 1996) also demonstrates that a minimum recording time of 2min is required for accurate results.

Table 5: Summary of HRV Indicators (Malik, 1996)

Indicator:	Description:	Stress Reaction:
Time Domain: Statistical Indicators		
Mean RR:	The mean RR interval value	Decrease
SD Deviation in RR:	Standard deviation in RR intervals	Decrease
RMSSD:	RMS of the sum of successive RR interval differences	Decrease
NN50:	RR intervals that differ by more than 50ms	Decrease
pNN50:	NN50 / total RR intervals	Decrease
Time Domain: Geometric Indicator		
HRV triangular index:	NN intervals / histogram height	Decrease
Frequency Domain Indicators		
LF/HF ratio:	LF power / HF power	Increase
HF power:	High frequency power spectral density	Decrease
LF power:	Low frequency power spectral density	Decrease

Frequency analysis involves breaking the Tachogram down into high and low frequency components. This is done using a standard fast Fourier transform (FFT), low frequency (LF) components and high frequency (HF) components are then quantified. The Power Spectral Density (PSD) of HF and LF components can be quantified, and from this (Schnell et al., 2013) shows that an approximation of the participants stress levels can be calculated. (Song et al., 2013, Sañudo et al., 2013) and (Hall.J, 2006) agree that LF components are measured between (0.04 – 0.15Hz), and HF components are measured between (0.15 – 0.4Hz). The LF/HF PSD ratio is thought to be related to the stress experienced by the individual. When a person becomes stressed, the influence of the sympathetic branch of the ANS increases on the heart while the parasympathetic influence decreases.

In time domain analysis mean RR and standard deviation are direct measurements of the R-R intervals. A lower standard deviation would mean that there is less variability between the intervals, meaning that HRV has decreased (Sandercock et al., 2005). Decreasing mean RR intervals imply that HR is increasing. There are very few research papers that directly evaluate ride comfort using physiological responses, once such researcher is (Yu-Kuang and Hwang, 2011), the research shows promising results, but focuses on EEG rather than ECG. Table 6 shows a summary of relevant studies that have previously been done. These studies are not directly linked to ride comfort, but are relevant because they use HRV as an indicator of physiological stress.

Table 6: Summary of research papers using HRV as a stress indicator

Researcher:	Tests:	Relevance to HRV:
(Sañudo et al., 2013)	Response during recovery from exercise	Passive low intensity WBV reduces HR, no significant effect on LF/HF ratio.
(Song et al., 2013)	Work efficiency test in cars vs trains	LF/HF ratio used as a physiological stress indicator. Found to be lower in cars than trains.
(Schnell et al., 2013)	Effects of environmental factors on HRV	Social stress, noise and CO levels are the main influencing factors for HRV
(Dijksterhuis et al., 2011)	Demand on lane keeping behaviour	HRV frequency domain of 0.1Hz used as an indicator of mental effort. HRV LF/HF used to indicate stress
(Piechulla et al., 2003)	Reducing mental workload by use of a man-machine interface	Decrease in HRV may correlate to indicate increased mental effort 0.07-0.14Hz

2.2.6 Environmental Effects on Physiological State

(Schnell et al., 2013) and (Hall.J, 2006) explicitly show that the environment has a direct effect on physiological state. Minimizing the effects that the surrounding environment may have on test participants is important for consistency and repeatability in these experiments. The environmental effects that can be mitigated relatively easy are sound, temperature and visual stimulus. (Schnell et al., 2013) shows that a loud and sudden noise can startle a human, inducing a sympathetic reaction.

Visual inputs can have a significant effect on physiological state, (Hall.J, 2006) shows that certain images or scenes can trigger emotional reactions. An environment that looks unsafe could cause a sympathetic reaction, preparing the body to enter a “fight or flight” state. (Hall.J, 2006) also demonstrates that variations in temperature can very easily cause discomfort in testing participants which forces a reaction from the ANS to maintain homeostasis.

2.3 Statistical Analysis

Statistical analysis is absolutely critical to any research project that involves a large set of data. The experimental procedures for this dissertation are documented in Sections 4 and 5. The two statistical evaluation methods used in data processing are random linear regression, and a 4-point crossover analysis. This section of the literature survey explores what the two types of analysis are, and how they are performed.

2.3.1 Statistical analysis techniques

A crossover analysis is typically used in pharmaceutical tests. (Delaney et al., 2009) describes the crossover study as a method by which participants act as their own controls. In the case of this research, a 4-point crossover study would involve subjecting all participants to 4 vibration signals, rather than splitting the participants up into 4 groups which each receive 1 vibration signal. This method eliminates the possibility of one group being more sensitive to vibration and skewing data.

Linear regression is simply the application of a "line of best fit" through a data set, random linear regression as defined by (McWilliams, 2014) is a simple linear regression model that is dependent on and input as well as a random (Stochastic) variable. This means that the "Wrong" answer serves as an approximation for the next answer in an iterative process. Random linear regression allows large data sets that have multiple unrelated variables to be approximated.

2.3.2 Statistical Significance

Statistical hypothesis testing according to (Mohr, 1990) always works with a null hypothesis. The null hypothesis is the hypothesis data obtained is completely unrelated. When performing statistical significance checks a P value is calculated. This value is the probability of rejecting the null hypothesis (the smaller the p value, the less likely that the data is related). A P value of 0.05 or less is considered statistically significant, meaning that the statistical result has only a 5% chance of rejecting the null hypothesis.

2.3.3 Sample size calculations

In many cases, and specifically with this research, it may be necessary to determine the required sample size for the data gathered to be statistically significant. Work done by (Kadam and Bhalerao, 2010) shows that sample size may be determined using the equation:

$$n = \frac{2\left(Z_{\alpha} + Z_{1-\beta}\right)^2 \sigma^2}{\Delta^2} \tag{1}$$

In this equation Z_{α} and $Z_{1-\beta}$ are constants determined for each study, they are determined for a required confidence interval. The symbol Δ represents the expected change in a data set, and σ is the standard deviation of a recorded dataset. For a 95% confidence interval the value of $Z_{1-\beta}$ is 1.65 and the value of Z_{α} when selecting $P \leq 0.05$ is 1.65 (Kadam and Bhalerao, 2010).

For this research, a pilot study would need to be performed in order to determine the standard deviation in test participants. This would be done using a 4-point crossover analysis which would help to mitigate biodynamic variability. Sample size estimation for the main study can then be made using the standard deviation and mean results from the pilot study, where the mean result will be accepted as the expected result. The calculation will be done for a 95% confidence interval using P as 0.05.

2.4 Literature Survey Conclusion

The literature survey has explored several research papers over two disciplines. The researcher was unable to find many research papers that directly link physiological responses to ride comfort, but has found many papers that indirectly indicate it is possible.

It is known that the physiological state of human changes as external stimulus is applied, and that homeostasis must be maintained during WBV. In order to maintain homeostasis the ANS will need to regulate HR, BR and other physiological parameters. As a result, fluctuations in physiological stress may be indicative of WBV.

The literature that has been studied has led to several decisions being made about the experimental procedure, these are listed as follows:

- The testing platform will make use of a vibrating seat
- Breathing rate, heart rate and heart rate variability will be evaluated
- A pilot study will be performed before the main tests.
- The testing environment must be controlled and standardised for all participants
- The experiment must conform to the safety requirements set by ISO 13090-1
- A minimum signal duration of 2min is required to measure HRV

2.4.1 Research Question

If WBV is considered to apply physiological stress to the body, there must be a physiological response to this stress that can be measured. The fundamental question that this research aims to answer is whether or not the physiological response to a change in vibration is consistently measureable and statistically significant.

Chapter 3: Research Preparation

This chapter of the dissertation deals with all preparation required before any testing could be done. This includes considerations of safety, environmental effects, participant variability and the testing platform design. Each of these aspects is addressed individually as a separate section in the chapter.

3.1 Safety Requirements and Considerations

As expected, the safety of participants during the tests was the first priority. The testing platform was commissioned for safety by the researcher and all relevant supervisors before each testing day. To ensure that the test platform was safe and subjects the participant to minimal risk, the test platform was set up in accordance to ISO 13090-1 which is discussed in Section 2.1.5. To ensure that no participants are exposed to vibrations that may cause harm, the vibration signal severity was limited according to the standards requirements.

The requirements for failure were tested by simulating each type of failure. Risks to the test participant were reduced by using equipment which cuts hydraulic pressure to the actuator in the event of a fault. This safety mechanism proved to be safe in all cases of software and power failure, with one exception. In a case where the actuator still had power, but not the control system or computer used to run software, the actuator would stop moving but still have hydraulic pressure. This was deemed unsafe and to mitigate this, the observer present during testing would manually cut pressure to the actuator in the event of such a failure by means of a wall mounted switch. All failure scenarios met the safety requirements set in the standard.

The testing platform designed made use of a safety harness attached to the roof to prevent injury if a mechanical failure of the actuator occurred. The seat also has a safety belt to prevent the test participant from falling during vibration. As required by the safety standard the participant was also given an emergency stop switch. The standard operating procedure (SOP) for each day of testing is included in Appendix B of this document.

3.2 Environmental Effects Mitigation

The effects that the environment may have on the participant's physiological state have been mitigated and standardised as much as possible. Minimizing the effects that the surrounding environment may have on test participants is important for consistency and repeatability in these experiments. The literature survey in Section 2.2.6 identifies sound, vision and temperature as environmental aspects that can be controlled.

The sound from the surrounding environment is mitigated by providing each participant with a set of earplugs. All other tests in the vibration labs were temporarily stopped while testing was underway to reduce the level of noise. The temperature in the lab was regulated to 24°C to prevent variations in temperature between tests or participants. The general environment was standard for all participants entering the lab since the lab remained the same. The visual stimulus from activity within the lab was mitigated by blocking off the testing area with room dividers. The physiological effects of being exposed to a new activity (in this case an experiment) were mitigated by ensuring all participants received the same experience and were briefed by the same researcher.

3.3 Test Participants

Section 2.1.1 of this dissertation mentions biodynamic variability, which is always present in any tests involving human participants. The tests done in this research are no different, and are affected by not only biodynamic, but also physiological variations between participants. In order to mitigate this, some requirements were set for all volunteering test participants according to ISO 13090-1 (ISO, 1998). The testing done in this research was performed as a pilot study first, and then a main study, and the requirements for both groups only varied in age range as shown in Table 7.

Table 7: Participant Requirements

Requirement:	Pilot Study:	Main Study:
Age	23-30	20-27
Gender	Male	Male
No recent trauma	Yes	Yes
No active disease	Yes	Yes
No current medication	Yes	Yes
No prosthetics	Yes	Yes
No smoking	Yes	Yes

The participant requirements for the pilot and main study differ since the new age range made it easier to find participants at the university, the range itself from min to max in both cases remained the same. Only male participants were used to eliminate the physiological differences between male and female participants. The choice to use only non-smoking participants was made since reduced lung function can add to physiological stress (Hall.J, 2006), and participants that have been smoking for varied periods would have different states of health. All test participants are also required to sign an informed consent from that explains the test procedure and risks involved. The requirements such as being a non-smoker that each participant must adhere to are also included in the form. The Informed consent forms for both the pilot and main study are included in Appendix C.

3.3.1 Pilot Study

As explained by Chapter 4, the pilot study was performed before the main study in order to find the required sample size for the main study. Table 8 shows the summarised physiology of the ten participants used during the pilot study.

Table 8: Summary of Pilot Study Participant Physiology

Parameter:	Mean:	Standard Deviation:
Basic Body Composition:		
Height [cm]	177	5.7
Weight [kg]	73.9	8.6
BMI	23.7	3.2
Waist to Hip Ratio	0.94	0.03
Heart Health, Muscular Endurance and Flexibility		
HR after 3min step test [bpm]	119.5	10.4
Number of Pushups in 1min	43.5	13.5
Number of Situps in 1 min	34.5	14.2
Flexibility test [cm]	25.3	7.6

Each parameter evaluated in Table 8 is separated into one of two groups. The first group, basic body composition, forms an approximation of tissue mass and biodynamics. The parameters measured relate to the shape of the body. The second group deals with the fitness and endurance of the body, as well as the cardiovascular system. All measurements taken are standard measurements used in medical practice when assessing patient health.

3.3.2 Main Experiment

The main experiment made use of 60 volunteers rather than only 10, the larger sample size was necessary in order to find statistically significant data. Table 9 summarises the participants in the same way as was done for the pilot study.

Table 9: Summary of Main Experiment Participant Physiology

Parameter:	Mean:	Standard Deviation:
Basic Body Composition:		
Height [cm]	177.6	7.3
Weight [kg]	78.4	18.2
BMI	24.9	4.2
Waist to Hip Ratio	0.94	0.07
Heart Health, Muscular Endurance and Flexibility		
HR after 3min step test [bpm]	112	19.4
Number of Pushups in 1min	36	9.8
Number of Situps in 1 min	33	9.2
Flexibility test [cm]	22	10.3

3.4 Experimental Setup

As determined at the end of Chapter 2, the testing platform to be used is a vibrating seat. Since the University of Pretoria does not have access to a large vibrating platform as used by the University of Southampton, an alternative solution was required. It was decided that a vehicle seat would be mounted onto a hydraulic actuator in order to generate vibration. The seat would need to include a footrest, and conform to all applicable safety standards. This section of the dissertation deals with the design of the interface between the seat and actuator, as well as the generation of the vibration signals to be used.

A passenger vehicle seat was used since the seat was readily available. The choice to use a regular seat rather than a rigid seat or one without a backrest was made with the vibration transmissibility from the seat rail to the participant in mind. The vibrations experienced by a test participant in the seat would be very similar to the vibrations experienced during actual driving, including the effects of the seat cushion and backrest.

In the interest of closely simulating the vibrations experienced in an actual vehicle the decision was made to use measured vibrations from a colleagues tests as an input rather than a random road. The vibration displacement measurements were taken at the seat rail of the vehicle during testing done on a 4-poster(Grabe, 2017). These accelerations could be safely applied directly to the seat rail in these experiments by making use of the hydraulic actuator.

3.4.1 The Seat-Actuator Interface

The only challenge with the testing platform proposed is the need for a connection between the car seat and the actuator which is strong enough and does not add unnecessary vibrations. Since the health guidelines in ISO 2631-1 are only applicable up to 80Hz this would be the maximum frequency that the interface would be exposed to. The seat-actuator interface would also need to support a footrest and mounting points for a standard 3 point safety belt.

The conceptual design sketches for the seat-actuator interface before arriving at the final design are included in Appendix D of this document, where a variation of Concept 2 was adapted and used. The seat-actuator interface was required to be very stable, safe and easy to manufacture. The most important aspect of the design was ensuring that the natural frequencies of the interface all fall above 80Hz. ANSYS software (ANSYS, 2017) was used to achieve this, and the final result was built using mild steel in standard 120*80*3mm rectangular tubing, and 20*20mm square tubing. A special bolt was also required to connect the interface to the actuator itself, this was made from EN26 high tensile steel.

(ANSYS, 2017) software was used to simulate the natural frequencies of the structure, small changes in geometry and wall thickness were made until all natural frequencies of the model were above 80Hz. This ensured that the interface would never be excited at its natural frequency during normal testing conditions. Figure 5 shows the final model of the interface with its natural frequency at 81.97Hz, including the model geometry and mesh with the first mode shape.

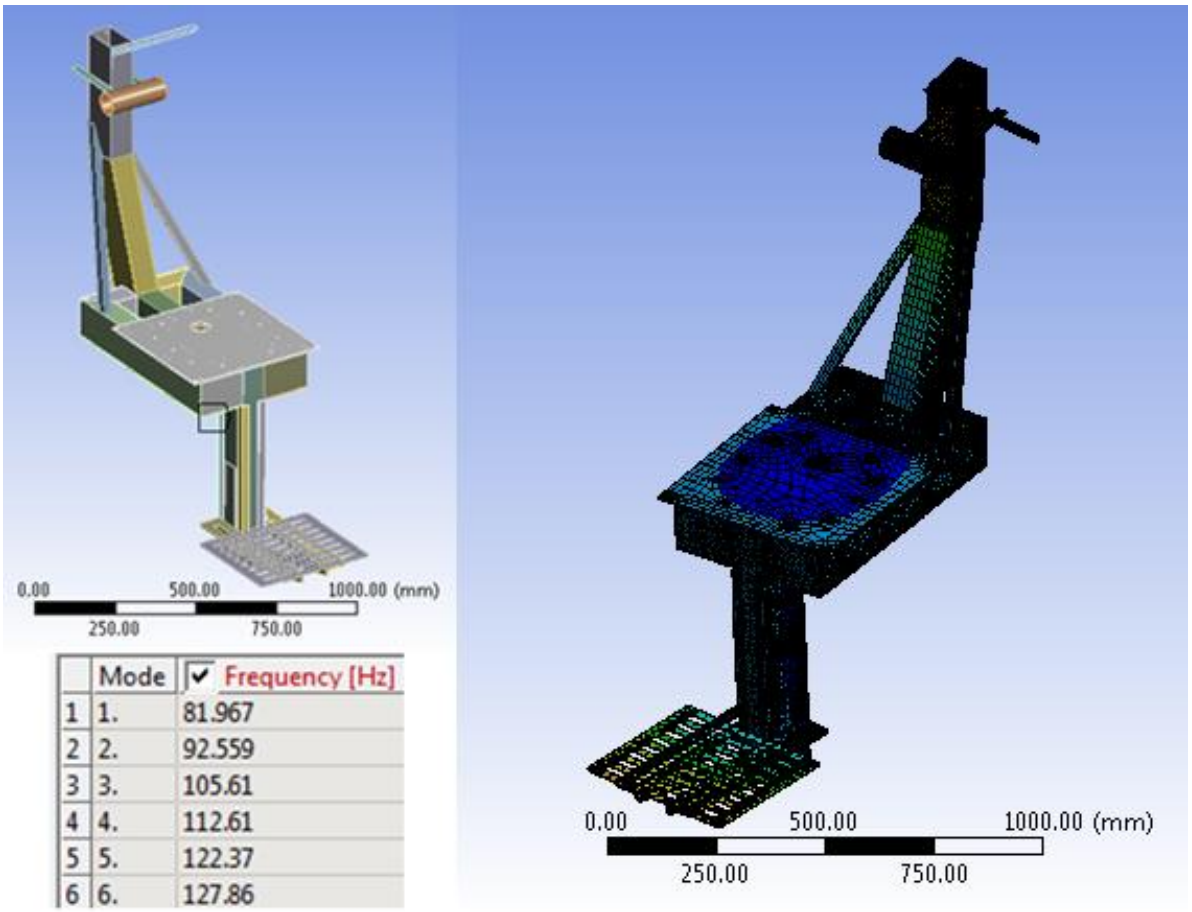

Figure 5: Seat-Actuator Interface Simulation (ANSYS, 2017)

Boundary conditions were set as realistically as possible, the bolt connection was modelled by setting only the areas of the seat rig that would be in contact with the bolt as fixed, and having a sliding joint present where the footplate extends downward to prevent the rig from spinning around the actuator as it moves. Figure 6 shows the bolt connection (A) and the frictionless sliding support (B) as they have been defined in the ANSYS software.

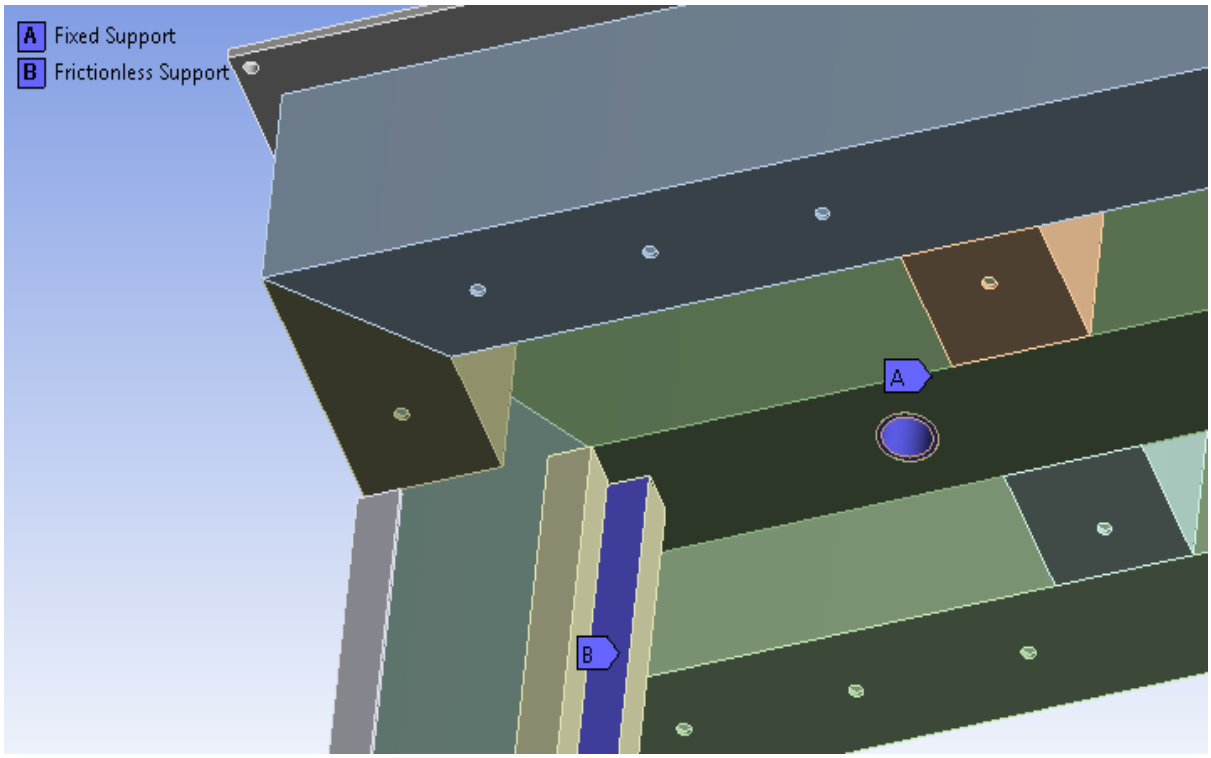

Figure 6: Seat-Actuator Interface Boundary Conditions (ANSYS, 2017)

The mesh for simulation was generated using sweep methods where available and made use of tetrahedral meshes in all other places. The mesh consists of approximately 84000 separate elements with an average quality of 0.51, this quality value is a number between 0-1 assigned by the ANSYS software to estimate mesh quality. The researcher acknowledges that the mesh used is not perfect, but when refining the mesh it was found that unlike mechanical stress/strain applications, the first natural frequency calculated did not change by more than a few decimal points. Because of this the mesh used was considered sufficient.

The first two natural frequencies identified on the interface occur at 81.97Hz and 92.56Hz respectively, and each have a rotational mode shape about the vertical axis. Natural frequencies 3 and 4 at 105.6Hz and 112.6Hz show the structure pivoting left and right, and forwards and backwards about the bolt connection point. Higher frequencies affect the footrest and safety belt mounting points.

Although the seat taken from the vehicle was chosen for the influence of the backrest and seat cushion, there is no set requirement on the specific vibrations applied by the actuator. As a precautionary measure it was decided that the maximum vibration frequency applied by the actuator would be limited to 40Hz. Figure 2 shows that human sensitivity to vibration quickly reduces as the frequency passes 40Hz, because of this the cut off frequency can also be justified.

3.4.2 Test Equipment

Table 10 presents a summary of all equipment used during testing and the equipment listed in the table has been split into three separate groups.

Table 10: Summary of Equipment Used

Equipment:	Use:	Details:
Hydraulic Control System:		
Actuator:	Actuator to induce vibrations	25kN Schenk
Valves:	Control flow to actuator	Serial No. 0622544 Schenk
Control System:	Control cube module for actuator	Control cube- unmarked
National Instruments PC:	User interface for Control Cube	No: Sasol 02
Accelerometers:		
Seat rail:	Measuring acceleration on seat rail	10G Crossbow CXL10LP3
Footplate:	Measuring acceleration on footplate	Seismic PCB: Model No 393B04
Seat Pad 1:	Accelerations on participant	Seat pad No 32995
Seat Pad 2:	Accelerations on backrest	Seat pad No S313A
Physiological Measurement:		
Zephyr Bioharness	Measurement of HR, BR and HRV	Strap around chest

The final testing platform is shown in Figure 7. Although the accelerometers are not present, the locations of the various accelerometers as well as the way the seat is connected to the hydraulic actuator are shown here.

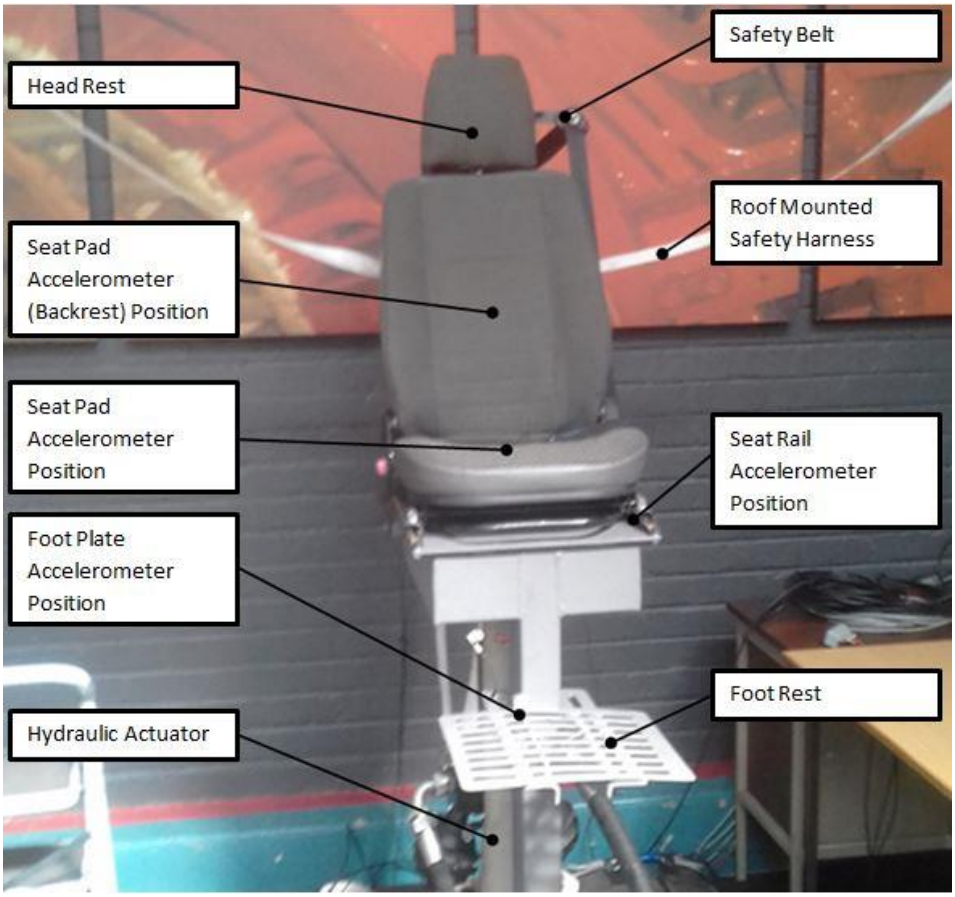

Figure 7: Finished Testing Platform

Chapter 4: The Pilot Study

This chapter documents the method of the experimental work done. It is important to note that the tests which were conducted involve human participants. Control and standardisation of such experiments are one of the biggest challenges researchers often face, therefore standardisation of these tests is absolutely critical. The experimental procedure for the tests done in this research is split into two sections. Before the main experiment was done, a pilot study was performed. The details for the main study are all included in Chapter 5.

4.1 Overview of experiment

The goal of this research was to determine whether or not physiological responses to vibration are consistent and statistically significant. The pilot study was performed to determine if there is a measurable physiological response to WBV in a vehicle environment. In order to achieve statistical significance the pilot study was also used before the main experiment to determine the required sample size for the main experiment. The pilot study makes use of the 4-point crossover technique, in which 10 participants are each exposed to 4 variations in vibration severity.

When a test participant entered the lab, the participant would be seated and instrumented. The participants physiological state were recorded for 2min while there are no vibrations present, this served as a baseline measurement, and is called state 1 in the rest of this document. After state 1 is recorded the participant is exposed to a reference vibration signal, the participants physiological state is again recorded for 2 min during the reference signal. This vibration signal is always identical for all participants and is called state 2. After this, there is a 30s pause before the participant is exposed to a third, alternative vibration signal. This alternative signal varies between participants for different vibration severities, and is recorded for 2 min as state 3.

It was recognised that after entering the “fight or flight” state the human body takes some time to recover. Consulting (Hall.J, 2006) the researcher found that this recovery period can vary significantly between two individuals and is difficult to quantify. Considering this it was decided that the need to wait for participants to return to a normal state could be eliminated by performing one test a day at the same time each day, rather than several consecutive tests during one day. Each group of vibration signals making up the vibrations a participant is exposed to during states 1, 2 and 3 are called a vibration set. The pilot study makes use of sets 1 to 5 with variations in vibration severity only during the state 3 physiological measurements.

For the pilot study, there should be 4 vibration sets for the 4-point crossover statistical evaluation. The researcher was concerned that there might not be a usable physiological response to smaller vibrations and decided to add a 5^{th} signal variation which was larger. The pilot test was performed over a period of 5 days and each participant was evaluated for states 1, 2 and 3 during a single test performed each day. On the first day all participants were exposed to set 5, but thereafter the participants were all exposed to random vibration sets each day. By day 5 of testing all 10 participants had been exposed to all the vibration sets. Physiological changes were evaluated within each set between states 1-2 and 2-3 to determine if there was a physiological response to vibration.

4.2 Vibration Signal Generation

The vibration signals as discussed in Section 4.1 are represented as 5 vibration sets. The vibration signal used from (Grabe, 2017) as discussed in Section 3.4 is 20s in length, and a vibration signal of at least 2min long is required in order to measure HRV. The original 20s signal recorded is summarised in Table 11, and it was extended to 120s by converting it into the frequency domain and from that generating a new signal as described in ISO 8608 – Mechanical vibration – Road surface profiles – Reporting of measured data (ISO, 1995).

Table 11: Summary of Original 20s Vibration

Parameter:	Value:
Max displacement up [mm]	43.4
Max displacement down [mm]	20
Max velocity [m/s]	0.38
Max acceleration [m/s^2]	6.02
Weighted RMS acceleration [m/s^2]	1.14

The 20 second signal is first converted into the frequency domain and its displacement Power Spectral Density (PSD) is plotted, this is shown in Figure 8. With the PSD successfully generated it is possible to calculate the amplitude *A* with the equation:

$$A(f) = \sqrt{PSD(f) \times 2 \times {}^{fs}/_{Nfft}} \tag{2}$$

This provides the magnitude of the PSD but does not include any phase information. In order to fully generate a new PSD that fits the original a new random phase must be generated. The new signal in the frequency domain is expressed as:

$$F = a + (i \times b) \tag{3}$$

Where:

$$a = A \times \cos(\emptyset) \tag{4}$$

$$b = A \times \sin(\emptyset) \tag{5}$$

In this case $\emptyset$ is the new randomly generated phase information. This new regenerated PSD is plotted over the original PSD to confirm that the extended vibration signal is still the same. It is immediately noticed that the new displacement does not begin and end at 0mm displacement. This is very important to prevent the actuator from reaching high accelerations when running the signal. The issue is resolved by multiplying the signal with a time domain signal that is equal to 1 in the middle, 0 for the first and last second, and steadily ramps between 0 and 1 over a period of 5 seconds.

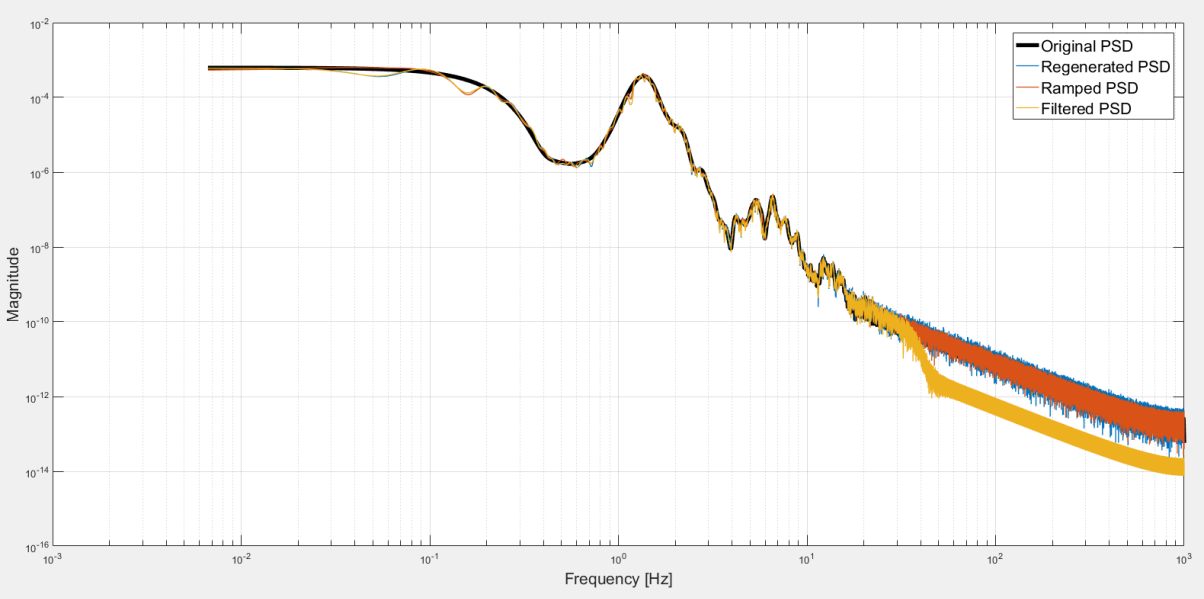

Figure 8: PSD Comparisons as Signal is Generated

Once the signal was modified to ensure that it starts and ends at 0mm displacement it was realized that there was a lot of high frequency energy in the signal. A 40Hz low pass filter is applied to the signal and the final PSD plotted onto the same Figure 8. Although there are some slight differences, the general form of the new signals PSD is the same, with a very clear drop off due to the 40Hz low pass filter. With this process complete the new extended reference signal of shown in Figure 9 having a duration of 120s and a very similar PSD.

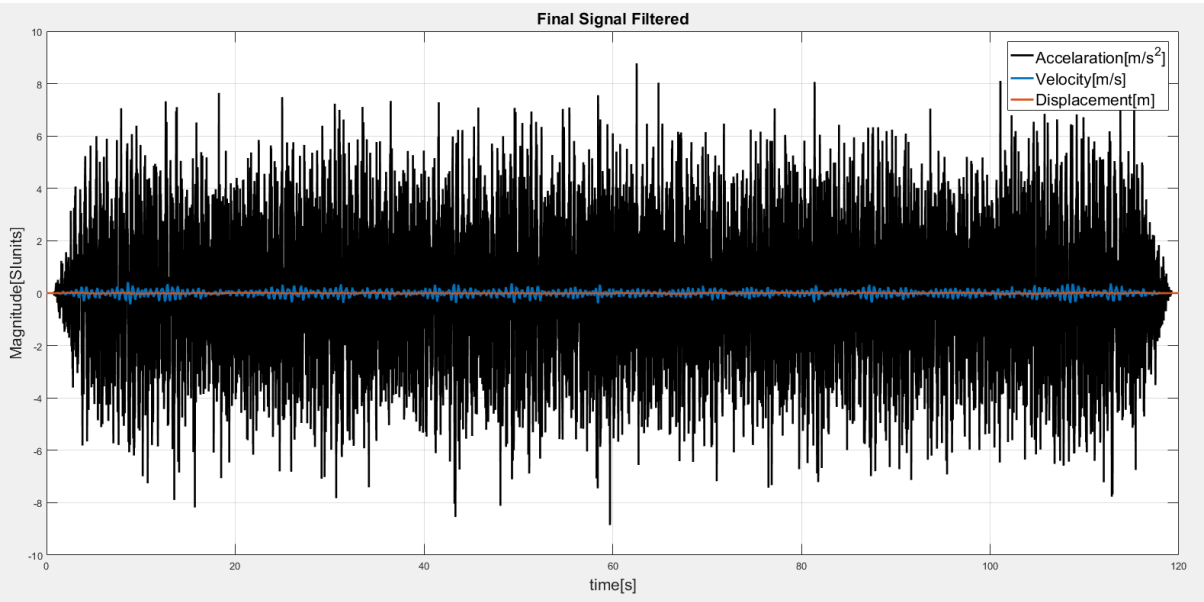

Figure 9: 120s Reference Signal (Pilot)

A summary of the new reference signal is shown in Table 12, and when compared to the original 20s signal there are some significant differences in the signal for displacement, velocity and accelerations. The vibration signal is clearly not the same, and only has an equivalent PSD.

Table 12: Summary of regenerated 120s Signal

Parameter:	Value:
Max displacement up [mm]	48.3
Max displacement down [mm]	43.9
Max velocity [m/s]	0.43
Max acceleration [m/s^2]	8.85
Weighted RMS acceleration [m/s^2]	2.07

With the reference signal in place it is now necessary to generate the 5 signal sets by increasing the amplitude of the alternative signal in each set. Table 13 shows the % increase in vibration amplitude corresponding to the percentile of people that will recognise the increase. This data is from (Grabe, 2017) for the specific 20s signal that was used. Following this table for set 1, the alternative signal has an amplitude which is 6.47% larger, but the same frequency content and 25% of the test subjects are expected to react to this change. The vibration signals for each set are converted into one long signal of 4min and 30s, since a 30s pause is included between state 2 and state 3. All vibration sets crated conform to the safety requirements.

Table 13: Amplitude Increases in Alternative Signals

Signal Set:	Percentile of people able to recognise difference:	% increase in amplitude:
1	25	6.47
2	50	9.57
3	75	14.64
4	95	22
5	-	30

4.3 Data Processing and Results

This section of the chapter deals with the processes and methods used to evaluate the data gathered during testing. It is split into checking what vibrations the test participants were exposed to, and then evaluating the physiological effects of these vibrations.

4.3.1 Signal Checks

Before any data processing can be done for the HRV data collected, it is important to check that the signal experienced by the participants is indeed the intended signal. This was done by comparing the intended signal displacement to the measured signal displacement as shown in Figure 10

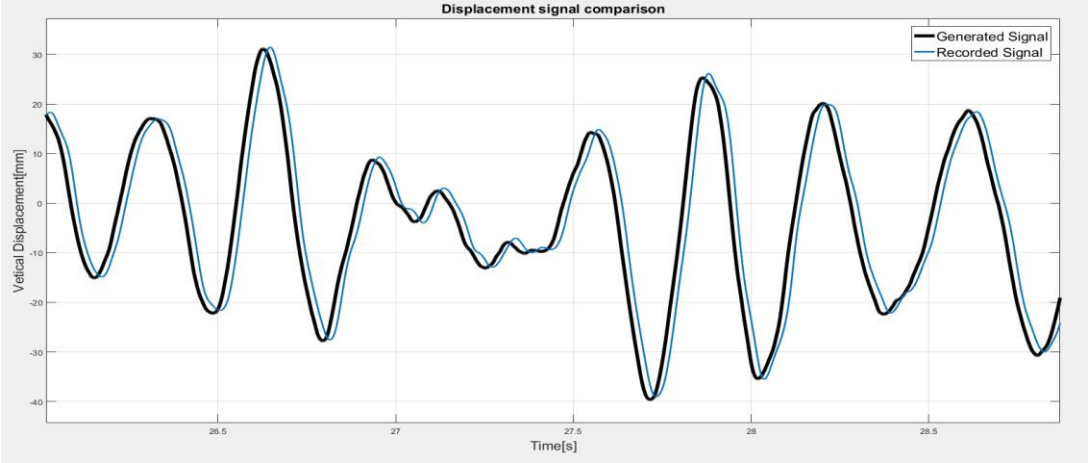

Figure 10: Signal Displacement Comparisons (Pilot)

Closer inspection of the graphs revealed that the signals were similar, but the actuator was not matching the full intended displacement and had some lag. A brief discussion with the Sasol vibration lab supervisor at the University of Pretoria resulted in the assumption that the PID controller for the actuator was not adequate. The PID controlled for the actuator was improved before the main study was performed, resulting in better correlations between the intended and recorded signals as shown in Section 5.3.1.

4.3.2 HRV Processing and Results

All HRV evaluations were done using Kubios. This software was selected to perform the data processing since it is readily available at the University of Pretoria and is able to perform the necessary operations. After being processed in Kubios, the data was plotted and presented using Matlab. The software calculates a wide range of HRV indicators automatically and easily processes the data gathered by the Zephyr Bioharness, this data is then plotted in Matlab. The pilot study is not the main focus of this research, and as such carries less detail than the main study.

Figure 11, Figure 12 and Figure 13 show the third state data for three of the HRV indicators used, this data is summarised in Table 14. The pilot study is not the main focus of this research, and therefore not all data is shown. This data has been selected to show how the physiological parameters of state 3 across all 4 sets do not steadily increase as expected. Within a single data set there was always an increase in HRV from state 1-2, but this was not always true for state 2-3.

Table 14: Summary of Mean HRV Indicators

	Set 1	Set 2	Set 3	Set 4
LF/HF	1.96	2.0	3.85	3.49
pNN50	7.59	2.81	14.14	4.57
RMSSD	0.029	0.024	0.033	0.023

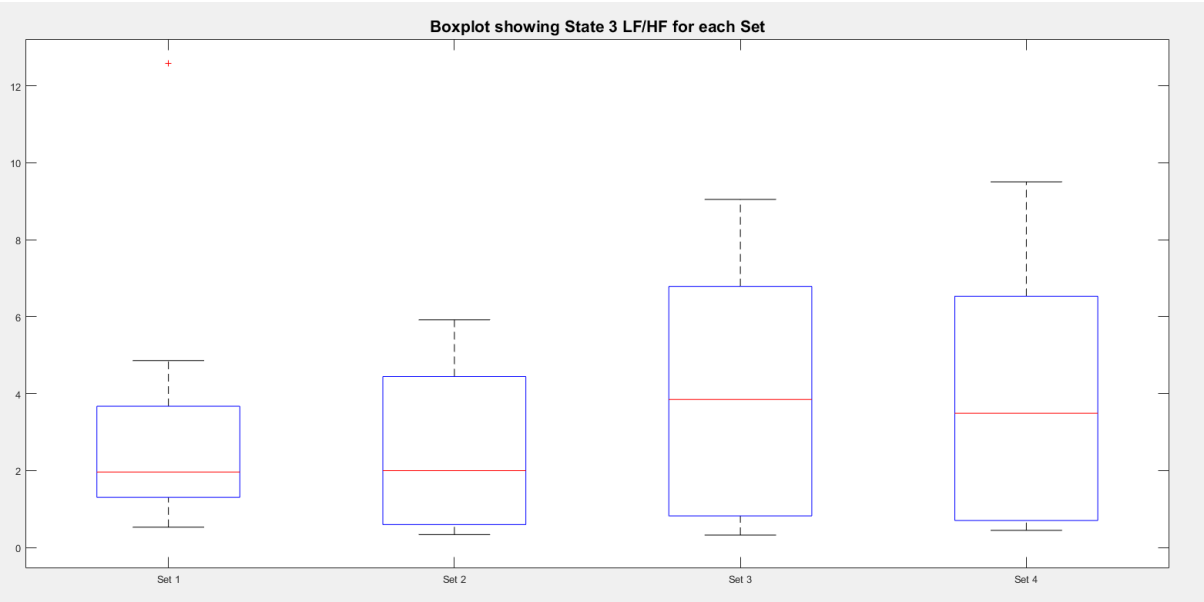

Figure 11: Boxplot Showing State 3 LF/HF Values

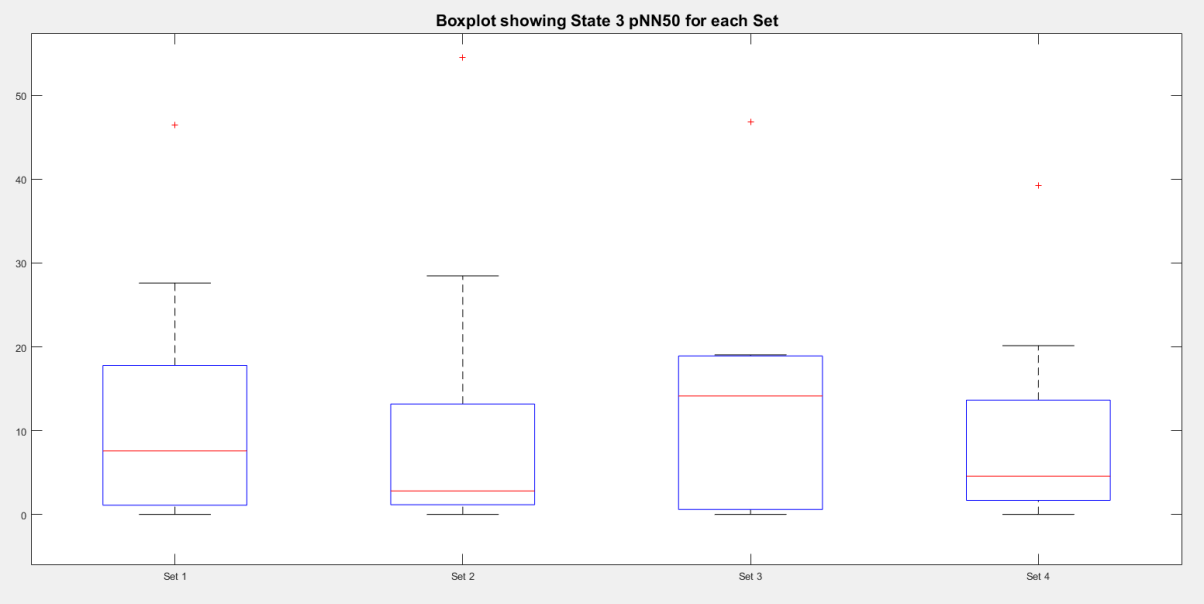

Figure 12: Boxplot Showing State 3 pNN50 Values

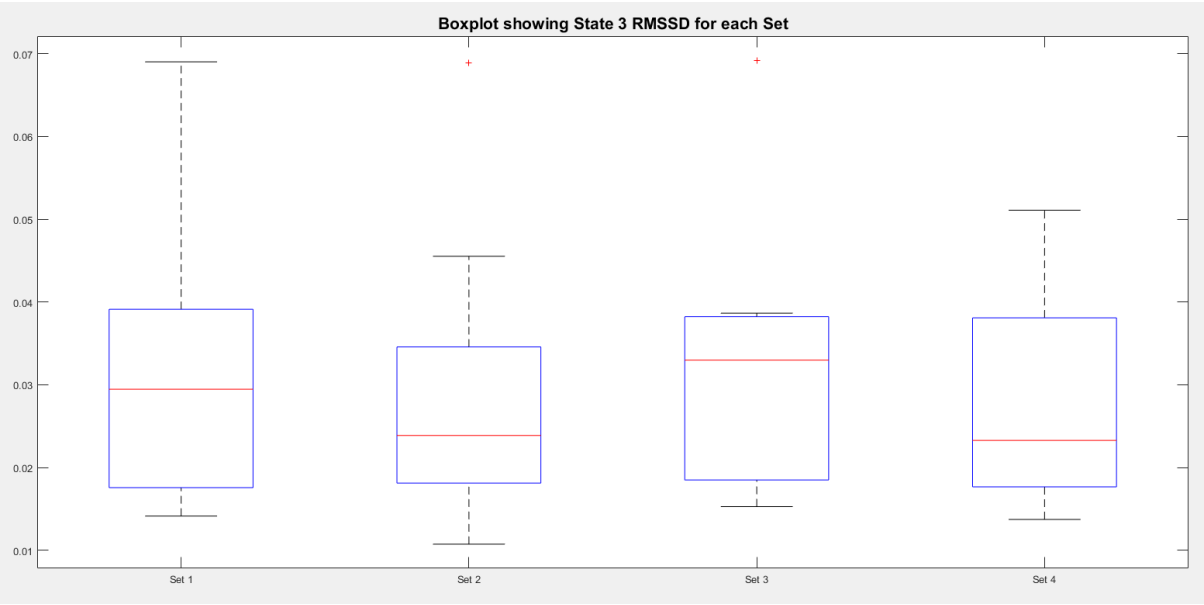

Figure 13: Boxplot Showing State 3 RMSSD Values

The data shown excludes set 5 since sets 1-4 all recorded changes in the physiological state of the participants. For LF/HF values Δ and σ are 1.33 and 4.2 respectively.

4.4 Discussion

The initial conclusion for the pilot study is that there is a physiological reaction to WBV, but this reaction cannot be correlated to the change in vibration. The pilot study also showed how the main study could be improved. The PID controller for the actuator was improved before the main experiment took place. Consultation with DR Grant revealed that extending the vibration signals for each state to 2 and a half min instead of 2min would improve HRV measurements. The 4-point crossover analysis was used in conjunction with Eq1 from section 2.3.3 to determine that a minimum of 52 participants would be necessary to find statistically significant data in the main experiment.

Chapter 5: The Main Experiment

This chapter deals with the main experiment, where analysis or processes are the same as the pilot study they are just mentioned rather than fully discussed. As with the pilot study, all testing equipment and vibration signals adhered to the relevant safety standards.

5.1 Overview of Experiment

The procedure and concept for the main experiment is very similar to the pilot study. The main experiment differs by making use of 60 participants which are each exposed to a random vibration set. Each participant is exposed to only one vibration set, and the sets are distributed evenly so that 15 participants are exposed to each set. The states 1-3 an sets 1-4 remain the same with the exception that all vibration signals have been extended to 150s, and the baseline period is now 300s.

5.2 Vibration Signal Generation

The vibration signal was generated using the same methods presented in Section 4.2. Table 15 shows a summary of the vibration set 4, the table shows that the total VDV for the entire vibration duration, as well as the weighted RMS acceleration, are within safety requirements. The full signal with state 2 and 3 vibrations is shown in Figure 14.

Table 15: Summary of the Full Vibration Set 4 (Main Experiment)

Parameter:	Value:
Max displacement up [mm]	62.8
Max displacement down [mm]	57
Max velocity [m/s]	0.55
Max acceleration [m/s^2]	10.81
Weighted RMS acceleration [m/s^2]	1.65
Estimated VDV [m/s$^{1.75}$]	9.62

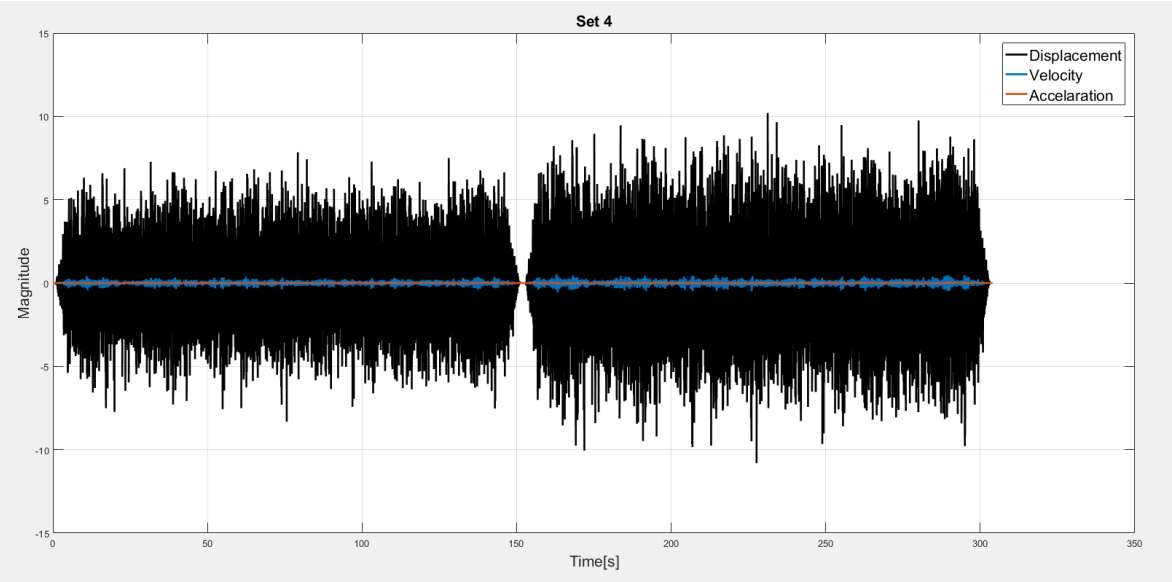

Figure 14: Set 4 Vibration Signal Showing State 2, State 3 and the 30s Pause

5.3 Data Processing and Results

In the main study data processing was done the same way, making use of Kubios and Matlab. The data processing and results in this section differ since the results are explored in greater detail. Data will be presented as block diagrams generated in Matlab and then summarised in table format. Although it was not a focus of this study, limited EEG data is included in Appendix E of this document. The EEG results were gathered for only one group of participants during the pilot study and are therefore not statistically significant, the data is included for the trends present.

5.3.1 Signal Checks

With the PID improvement a more robust check is required to evaluate what kind of vibrations the test participants are experiencing. This was done by comparing the intended vs actual signal for both displacement seen in Figure 16 and acceleration seen in Figure 17. The displacement with the new PID controller is very close to the intended displacement, having a slight lag and reduced amplitude. The acceleration on the other hand has much more significant amplitude reduction. This is explained by the mechanical impedance as a result of the participant's weight.

The accelerometer readings taken in various directions are all measured and plotted in order to better understand the vibrations that the participant is experiencing. The axis directions used correspond to those defined in ISO 2631-1 as shown in Figure 15.

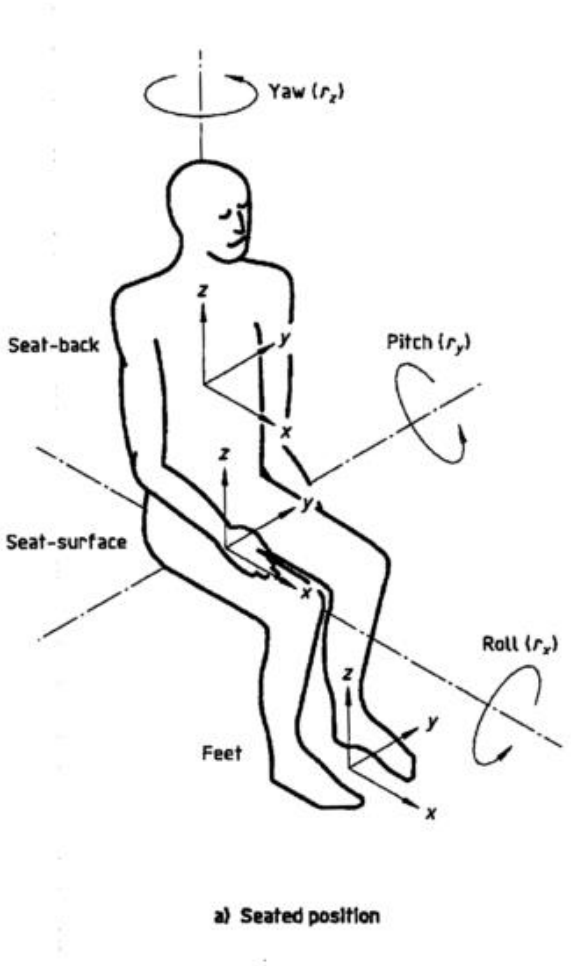

Figure 15: Axis Directions Defined by (ISO, 1997)

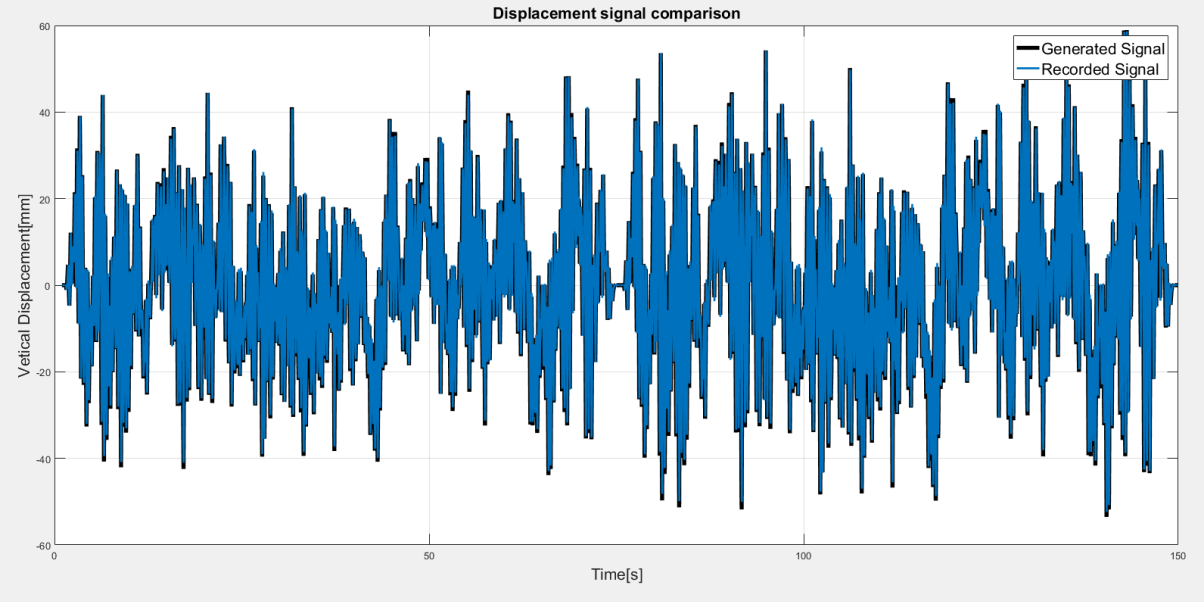

Figure 16: Displacement Comparison

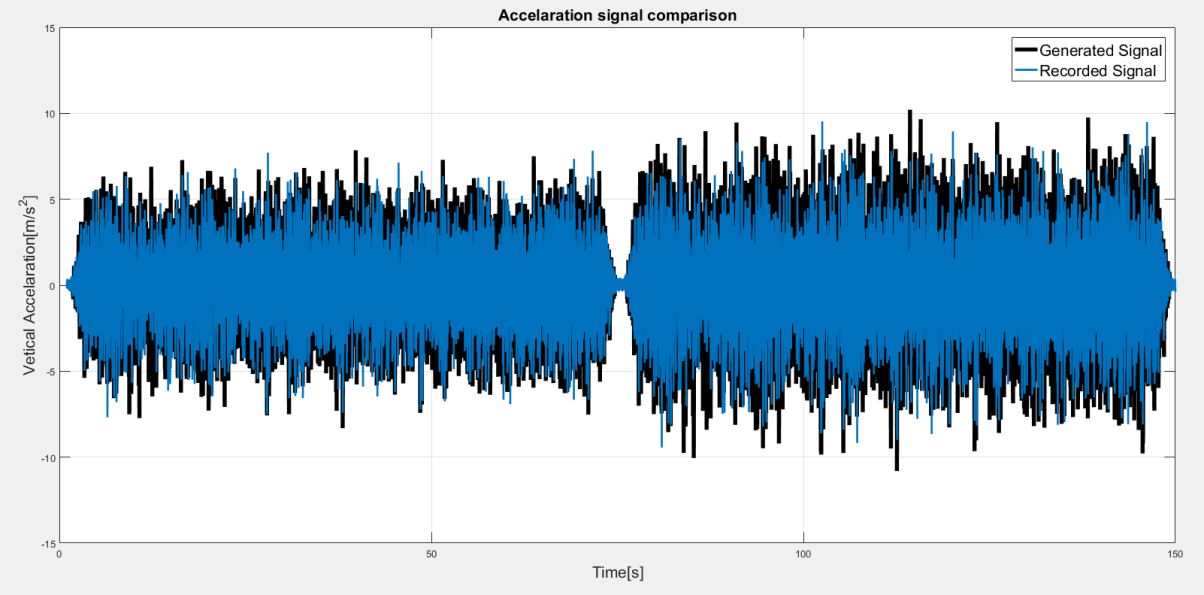

Figure 17: Acceleration Comparison (Seat Rail Z)

The accelerations for set 4, state 3 are used for all the following vibration direction comparisons. Figure 18 compares the seat rail to the seat pad which highlights the effect of the seat cushion transmissibility as the unweighted RMS acceleration reduces by 0.53m/s^2. Figure 19 compares the seat rail to the backrest accelerations in the Z direction, while Figure 20 compares accelerations between the seat rail and foot rest. The backrest was found to have only slightly more vibrations with an unweighted RMS acceleration increase of 0.1 m/s^2. The vibrations from the seat rail and footplate are very similar, with the footplate having an unweighted RMS of 0.01 m/s^2 more.

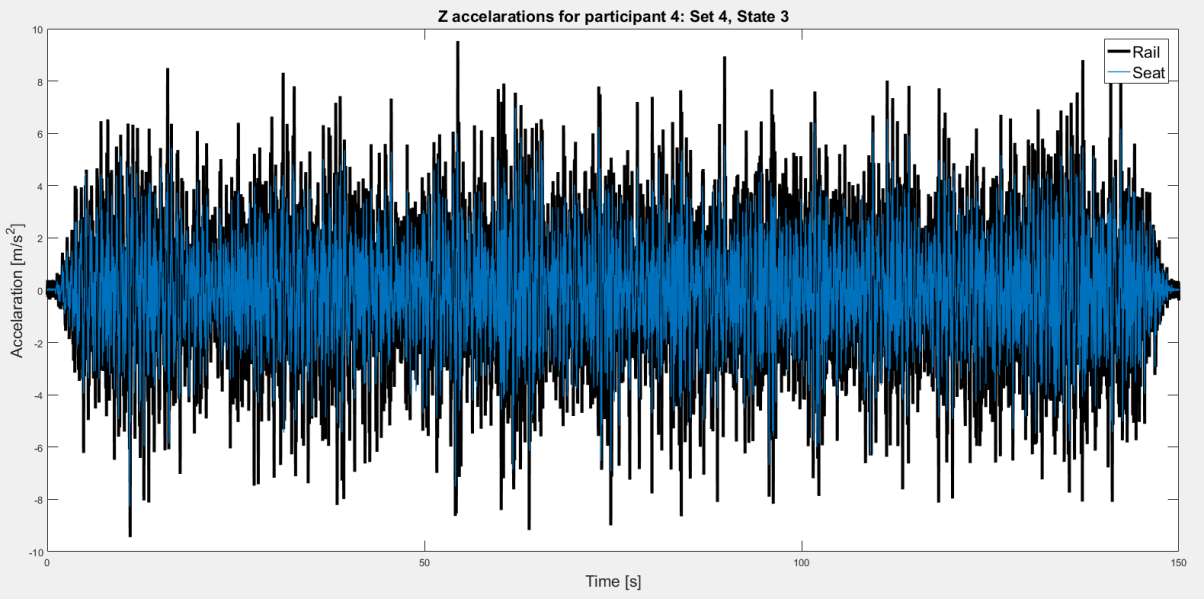

Figure 18: Z Acceleration Comparison between Seat Rail and Seat Pad

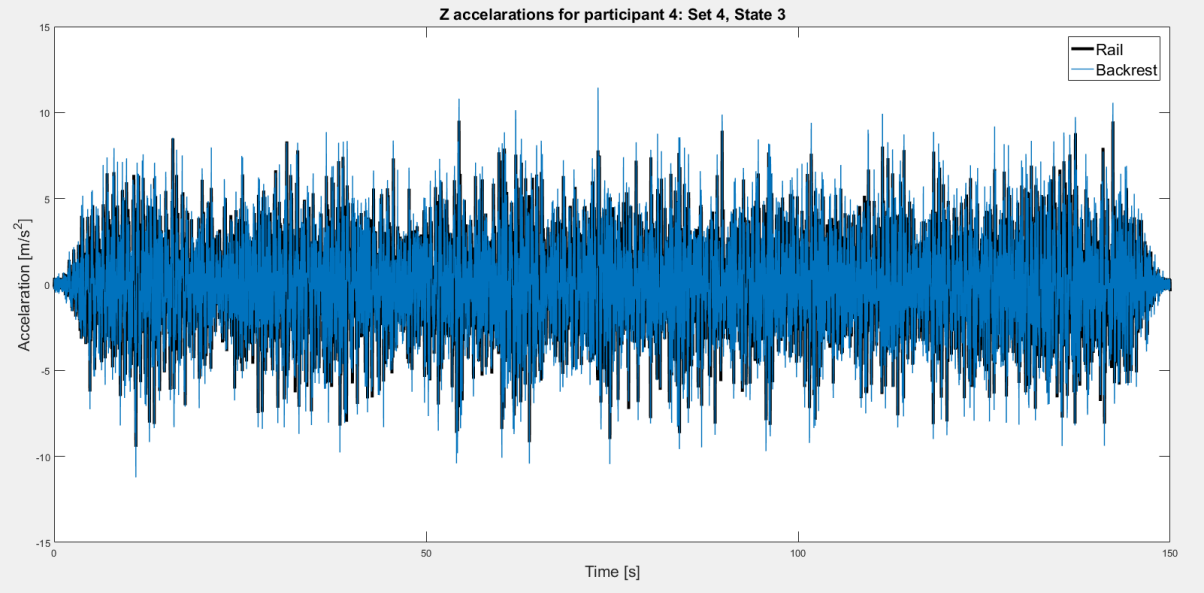

Figure 19: Z Acceleration Comparison between Seat Rail and Backrest

The next directions to be evaluated are along the X and Y axes. Figure 21 shows a recording of the Y axis vibrations present. Due to channel limitations on the data acquisitioning system only one accelerometer in this direction could be measured. Figure 22 shows a comparison of accelerations in the X direction for the seat pad and backrest. It is interesting to see that in this case the backrest vibrates less, with an unweighted RMS acceleration change of 0.14m/s^2.

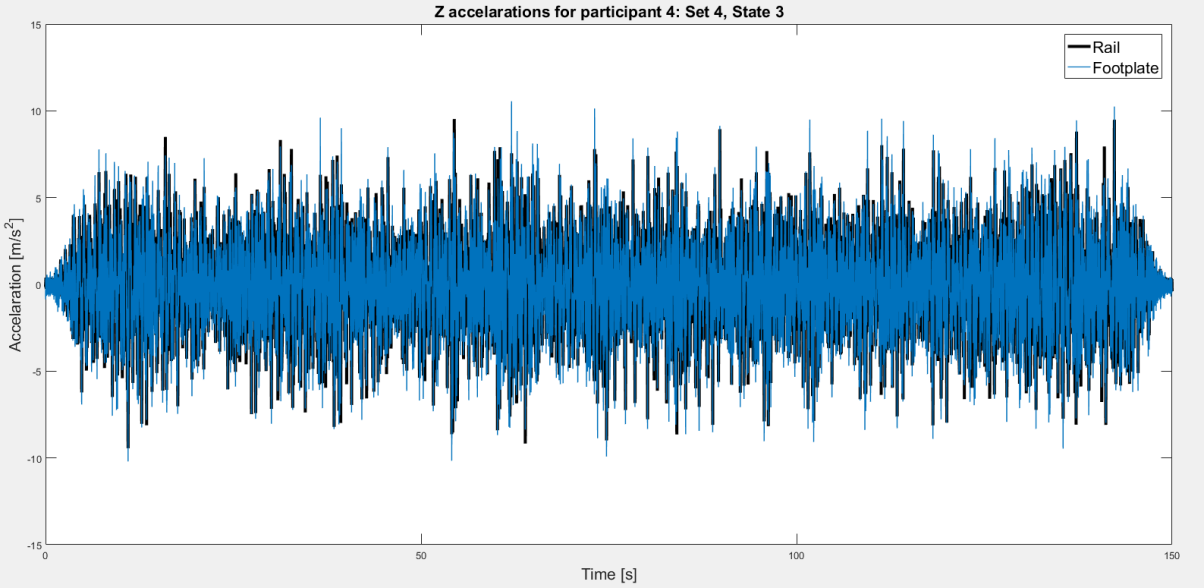

Figure 20: Z Acceleration Comparison between Seat Rail and Footplate

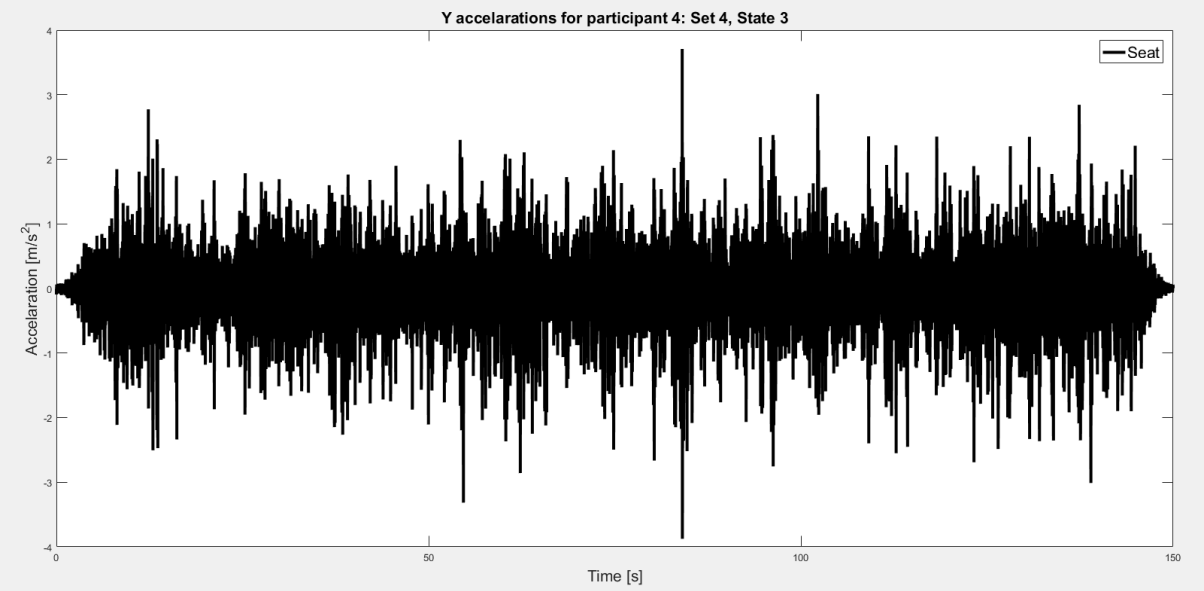

Figure 21: Measured Y Acceleration of Seat Pad

The weighted RMS accelerations for all of these measured accelerations are included in Table 16. These accelerations measurements show that the vibrations from the backrest are substantial, and certainly contribute to the perceived vibration severity of each participant. The weighted vertical acceleration at the seat pad is also low, proving the safety of the vibrations participants were exposed to.

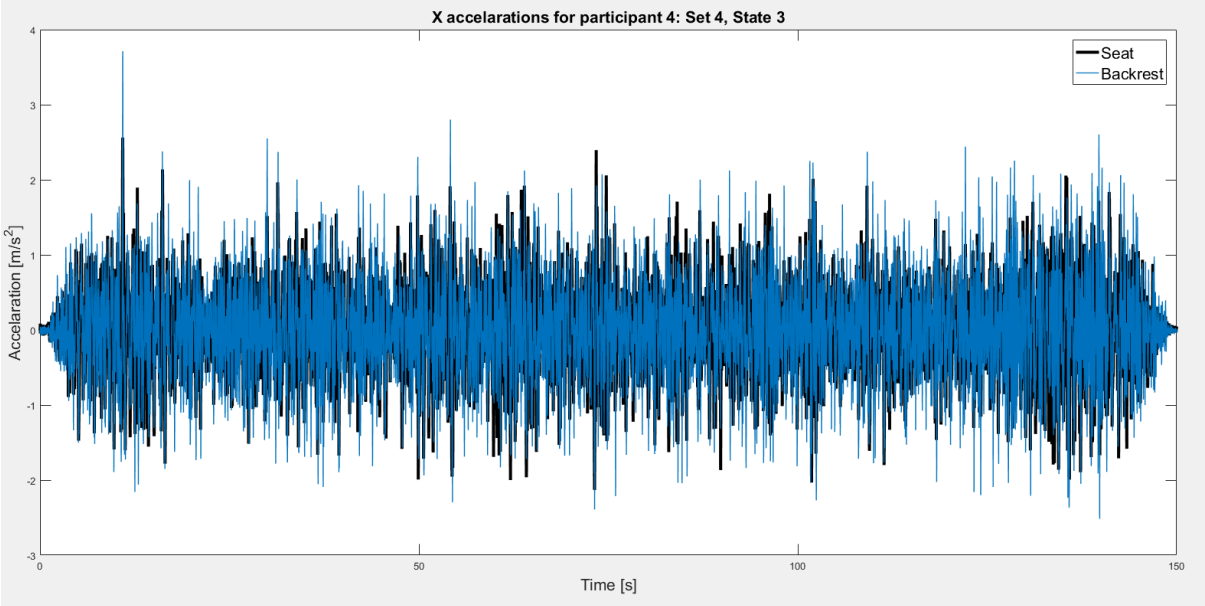

Figure 22: X Acceleration Comparison of Seat Pad and Backrest

Table 16: Weighted RMS Accelerations in X, Y and Z Directions for Participant 4

Signal:	Weighted RMS [m/s^2]
Z seat pad	1.53
Z seat rail	2.09
Z foot rest	0.85
Z backrest	0.56
Y seat pad	0.37
X seat pad	0.11
X backrest	0.52

5.3.2 Calculation of Overall Ride Comfort

According to ISO 2631-1 (ISO, 1997) an overall ride comfort value can be calculated by considering vibrations in the X, Y and Z directions. The equation for this calculation is:

$$a = \sqrt{RMS_Z^2 K_Z^2 + RMS_Y^2 K_Y^2 + RMS_X^2 K_X^2} \quad (5)$$

Where Kz, Ky and Kx are the factors 1, 1.4 and 1.4 respectively. This gives an overall ride value of 2.1m/s^2 for participant 4 during vibration set 4, state 3. The overall mean ride value for each vibration signal is shown in Table 17.

Table 17: Weighted Ride Comfort Summary

Signal –State 2:	Overall Ride RMS [m/s^2]:	Signal – State 3:	Overall Ride RMS [m/s^2]:
Set 1	1.42	**Set 1**	1.51
Set 2	1.41	**Set 2**	1.53
Set 3	1.43	**Set 3**	1.62
Set 4	1.42	**Set 4**	1.68

From the data in Table 17 it is clear that the backrest, as well as the X and Y vibrations experienced by the participant have a notable effect on the overall ride comfort experienced by the test participants. When evaluating mean ride comfort for all participants during vibration set 4, state 3, the average ride value for the Z direction alone is 1.53 m/s^2, while the overall ride value is 1.68 m/s^2. The overall ride values will be used when evaluating physiological responses.

5.3.3 HRV Processing and Results

The HRV analysis is done using the R-R tachogram from the bioharness. The extension of the main study vibration signal allows for more accurate results to be measured using Kubios. The software works with Matlab by evaluating the tachogram and saving the HRV results as a Matlab structure. This can then be easily accessed by the researcher for data processing.

Figure 23 shows a screenshot from the Kubios interface, the full 2.5 min tachogram for participant 1's state 3 is shown in the top window. There is a 2 min analysis window highlighted in yellow that gets shifted onward by 10s after each analysis to allow 4 calculations for each 2 and a half min signal. The line shown in red is a smoothing function used by the program to ensure that there are no movement artefacts in the data.

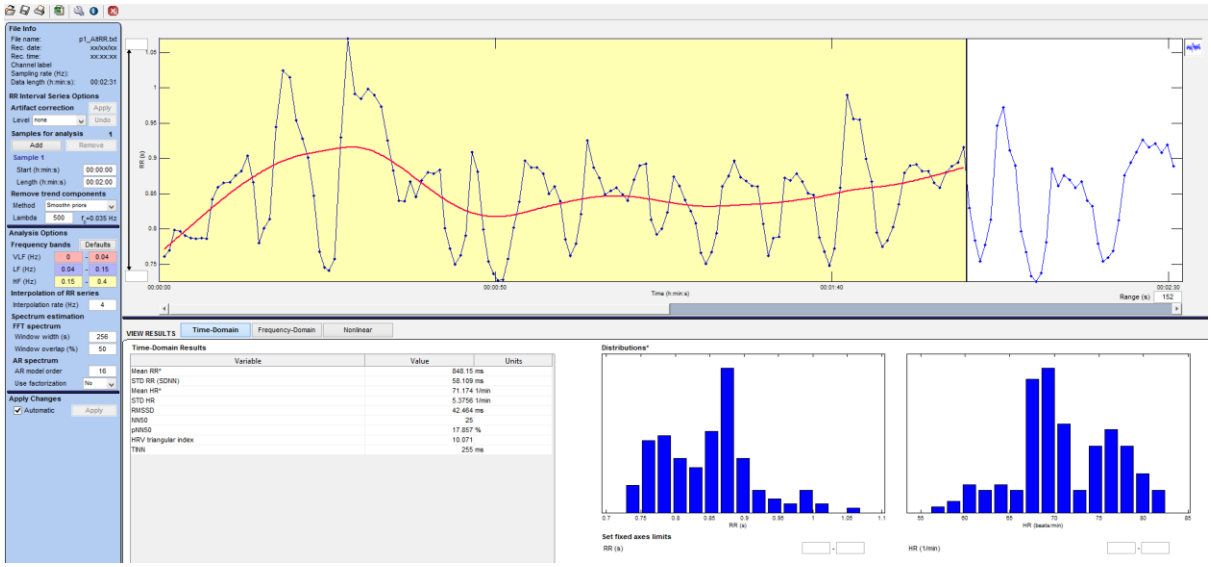

Figure 23: Kubios Analysis

The two histograms on the right are generated from the selected data and show the spread of R-R intervals as well as the spread of HR in beats/min over the measured time period. Once the four windows are evaluated using Kubios, the data from all 4 windows is averaged to give a single value for each of the physiological parameters. This means that there will be three LF/HF ratios for any given participant since a vibration set has three distinct vibrations. The 4 separate analyses with overlapping windows improve the reliability of the measurements. All HRV indicators are presented as a series of figures in Appendix F.

Table 18 summarises the mean values of all the measured data, including HR and BR. The figures are boxplots showing comparisons between state 1, 2 and 3 for all 15 participants and each relates to a specific HRV indicator. The trends present in Table 18 will be properly discussed in Section 5.4.

5.3.4 BR and HR Processing and Results

Breathing rate and heart rate were both evaluated by checking the average rate during each phase. These single average values for each participant are then evaluated as a boxplot, with one value for each participant. Figure 24 shows the generated boxplot for evaluated HR and there are 15 participants for each set. No clearly identifiable trend other than increased HR switching from state 1 to 2.

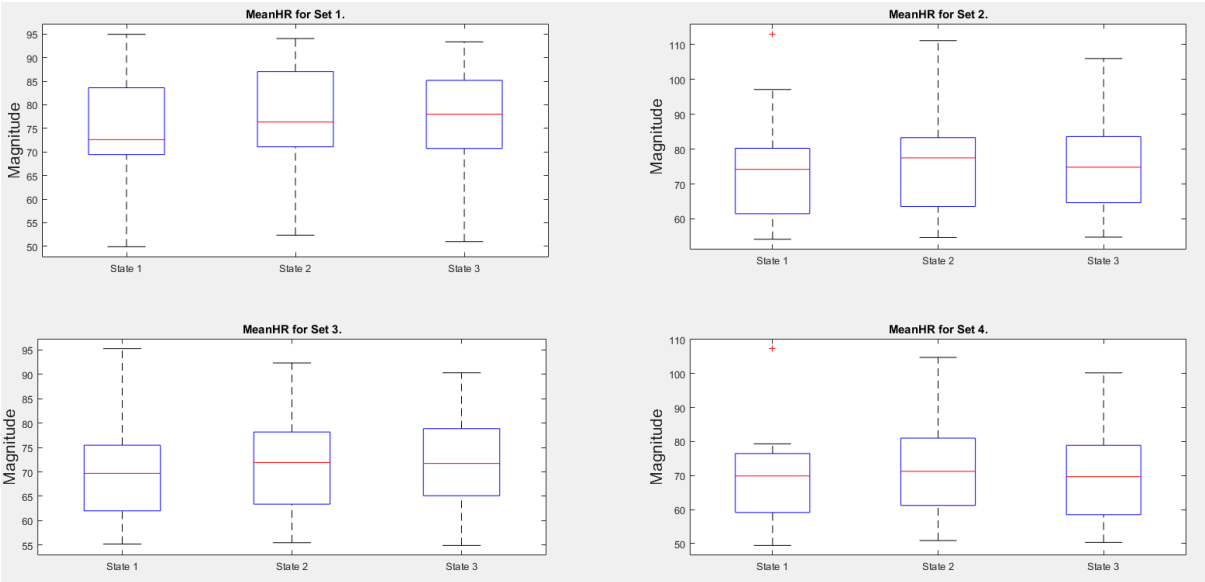

Figure 24: Boxplot for Mean HR

Figure 25 shows a similar boxplot for BR, which was generated in a different way. In this case a clearly increasing trend is seen from state 1 to 2. Similar to HR, the BR data does not consistently increase when switching from state 2 to 3. The mean values for set 4 seem to slightly decrease from state 2 to 3. This will be properly analysed in Section 5.4.

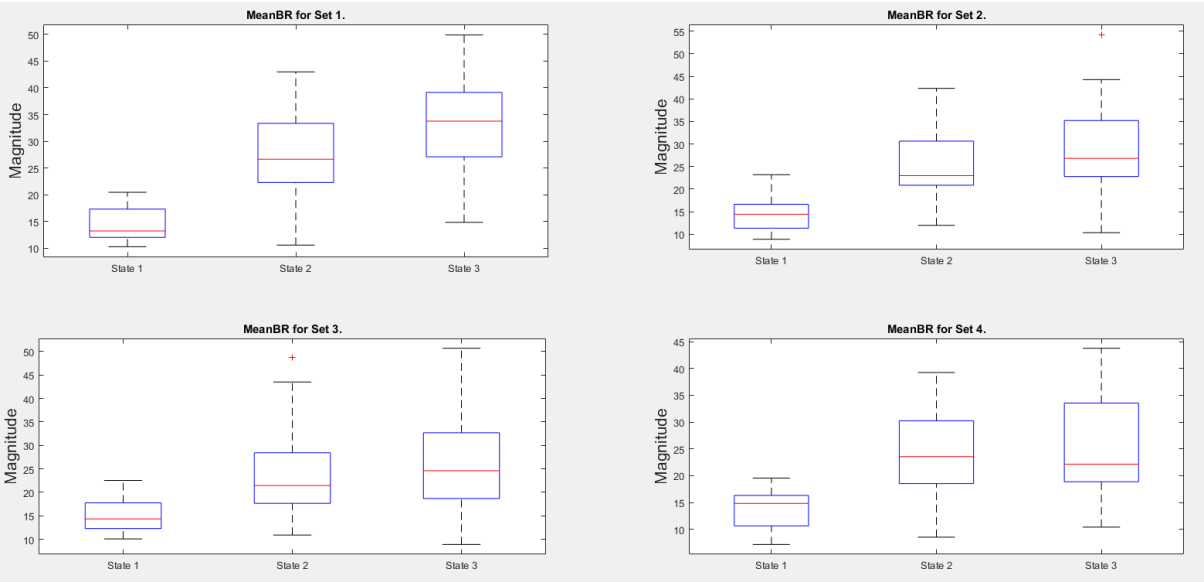

Figure 25: Boxplot for Mean BR

Table 18: Summary of all mean data: Note LF and HF are all *10-3

	Set 1:			Set 2:			Set 3:			Set 4:		
State:	1	2	3	1	2	3	1	2	3	1	2	3
LF/HF	1.19	2.86	2.53	1.46	1.53	1.80	1.09	1.42	2.17	0.90	1.24	0.74
LF	1.15	0.97	0.52	1.92	0.63	0.83	1.52	0.99	0.12	1.78	0.10	0.68
HF	1.59	0.51	0.39	1.41	0.71	0.63	1.55	0.92	0.51	2.24	0.70	0.48
HRV-Tri	12.0	9.98	8.83	14.2	10.6	9.96	12.2	9.59	10.2	13.4	10.9	10.1
Mean HRV	73.7	76.0	78.4	74.4	78.0	77.2	70.0	71.9	71.4	70.7	70.8	69.5
Mean RR	0.82	0.79	0.77	0.82	0.78	0.79	0.86	0.84	0.85	0.85	0.85	0.87
Sd HRV	5.74	4.75	3.76	6.29	5.02	5.79	5.66	4.45	4.34	4.91	4.65	4.66
Sd RR	0.06	0.04	0.04	0.07	0.05	0.05	0.06	0.04	0.04	0.06	0.05	0.04
NN50	48.8	58.3	21.8	57.0	30.3	30.3	48.0	27.8	23.0	55.8	38.3	34.5
pNN50	37.7	13.7	12.4	36.8	18.5	18.5	34.9	17.9	13.2	39.1	27.4	23.2
RMSSD	0.05	0.03	0.03	0.05	0.05	0.04	0.05	0.04	0.03	0.07	0.04	0.04
Mean HR	72.6	76.3	78.0	74.2	77.5	74.8	69.7	71.9	71.7	69.9	71.2	69.7
Mean BR	13.2	26.7	33.8	14.4	22.9	26.8	14.3	21.4	24.6	14.8	23.6	22.1

5.4 Statistical analysis and Discussion

The statistical analysis for each physiological parameter was performed using random linear regression. Each physiological parameter is evaluated and briefly discussed here. It is important to understand what is being evaluated in each case. The results from the statistical analysis for each parameter are presented in table format. Each table deals with the change from state 1 to state 2 from now on called delta A, and then with the change from state 2 to state 3, delta B. There is a delta A and a delta B value for each vibration set, and these values are compared to one another as well.

Since the conditions at states 1 and 2 are identical regardless of the set evaluated, one would expect there to be no significant change between sets for delta A. On the other hand state 3 varies between sets. Due to this it is expected that comparisons between sets for delta B will show statistically significant differences. For each delta there are comparisons between stages as well as states.

Another value included in the tables is the P value of each delta. The value indicates that a change is large enough to be considered statistically significant when it is less than 0.05. If data acquired is not statistically significant, it cannot be used in forming a research conclusion. Although trends may be present in a data set, it is important to understand that such trends are not reliable unless statistically significant. The expected statistical significance would be “yes” for all evaluations except for set comparisons for delta A. the expected delta values (Decreasing or Increasing) are evaluated according to Table 5.

Table 19: Mean RR Evaluation

State 1 - State 2 (Delta A):	Delta Values	P Value	P < 0.05
Set 1:	-0.0302	0.013	Yes
Set 2:	-0.0284	0.014	Yes
Set 3:	-0.0225	0.049	Yes
Set 4:	-0.0358	0.003	Yes
Delta Comparisons:			
Set 1 – Set 2:	0.0018	0.910	No
Set 1 – Set 3:	0.0078	0.635	No
Set 1 – Set 4:	-0.0055	0.739	No
State 2 – State 3 (Delta B):	**Delta Values**	**P Value**	**P < 0.05**
Set 1:	0.0056	0.502	No
Set 2:	0.0003	0.966	No
Set 3:	-0.0098	0.223	No
Set 4:	0.0195	0.071	Yes
Delta Comparisons:			
Set 1 – Set 2:	-0.0053	0.646	No
Set 1 – Set 3:	-0.0154	0.188	No
Set 1 – Set 4:	0.0139	0.235	No

Table 19 shows the expected statistical significance trends for delta A but not for delta B. Delta A also decreases as expected from state 1 to state 2. All expected behaviour is present for delta A, but no statistical significance is observed for B.

Table 20: RR Standard Deviation

State 1 - State 2 (Delta A):	Delta Values	P Value	P < 0.05
Set 1:	-0.0169	0.000	Yes
Set 2:	-0.0171	0.000	Yes
Set 3:	-0.0153	0.000	Yes
Set 4:	-0.0110	0.002	Yes
Delta Comparisons:			
Set 1 – Set 2:	-0.0003	0.958	No
Set 1 – Set 3:	0.0016	0.744	No
Set 1 – Set 4:	0.0059	0.235	No
State 2 – State 3 (Delta B):	**Delta Values**	**P Value**	**P < 0.05**
Set 1:	-0.0051	0.055	No
Set 2:	-0.0004	0.887	No
Set 3:	-0.0013	0.632	No
Set 4:	-0.0029	0.291	No
Delta Comparisons:			
Set 1 – Set 2:	0.0047	0.219	No
Set 1 – Set 3:	0.0038	0.308	No
Set 1 – Set 4:	0.0022	0.566	No

Delta A in Table 20 again shows all of the expected results, while delta B loses statistical significance. At this point in the evaluation it would seem that the body only reacts as expected during initial vibrations.

Table 21: Mean RMSSD Evaluation

State 1 - State 2 (Delta A):	Delta Values	P Value	P < 0.05
Set 1:	-0.0178	0.000	Yes
Set 2:	-0.0177	0.000	Yes
Set 3:	-0.0153	0.003	Yes
Set 4:	-0.0062	0.190	No
Delta Comparisons:			
Set 1 – Set 2:	0.0001	0.993	No
Set 1 – Set 3:	0.0025	0.711	No
Set 1 – Set 4:	0.0116	0.084	No
State 2 – State 3 (Delta B):	**Delta Values**	**P Value**	**P < 0.05**
Set 1:	-0.0059	0.064	No
Set 2:	0.0032	0.326	No
Set 3:	-0.0061	0.064	No
Set 4:	-0.0059	0.082	No
Delta Comparisons:			
Set 1 – Set 2:	0.0091	0.047	Yes
Set 1 – Set 3:	-0.0002	0.972	No
Set 1 – Set 4:	0.0001	0.983	No

With the exception of set 4 in Table 21, Delta A holds true for a third time. Unfortunately delta B also continues the same trend of losing statistical significance.

Table 22: Mean NN50

State 1 - State 2 (Delta A):	Delta Values	P Value	P < 0.05
Set 1:	-18.823	0.000	Yes
Set 2:	-12.195	0.002	Yes
Set 3:	-14.251	0.000	Yes
Set 4:	-10.614	0.006	Yes
Delta Comparisons:			
Set 1 – Set 2:	6.6274	0.215	No
Set 1 – Set 3:	4.5717	0.391	No
Set 1 – Set 4:	8.2086	0.127	No
State 2 – State 3 (Delta B):	**Delta Values**	**P Value**	**P < 0.05**
Set 1:	-2.7347	0.175	No
Set 2:	-3.4053	0.090	No
Set 3:	-6.8572	0.002	Yes
Set 4:	-3.4338	0.091	No
Delta Comparisons:			
Set 1 – Set 2:	-0.6705	0.813	No
Set 1 – Set 3:	-4.1224	0.159	No
Set 1 – Set 4:	-0.6990	0.807	No

Table 22 continues with identical trends to previous evaluations, but an irregularity is noticed for all physiological parameters evaluated up till now. The set comparisons for delta B in each case are not statistically significant, but also do not always follow the expected decreasing trend in Table 19, Table 20 and Table 21.

Table 23: Mean pNN50

State 1 - State 2 (Delta A):	Delta Values	P Value	P < 0.05
Set 1:	-13.8904	0.000	Yes
Set 2:	-9.5952	0.001	Yes
Set 3:	-11.7862	0.000	Yes
Set 4:	-9.0711	0.001	Yes
Delta Comparisons:			
Set 1 – Set 2:	4.2952	0.253	No
Set 1 – Set 3:	2.1042	0.587	No
Set 1 – Set 4:	3.7429	0.203	No
State 2 – State 3 (Delta B):	**Delta Values**	**P Value**	**P < 0.05**
Set 1:	-2.0182	0.163	No
Set 2:	-2.4834	0.086	No
Set 3:	-4.8168	0.003	Yes
Set 4:	-2.4721	0.090	No
Delta Comparisons:			
Set 1 – Set 2:	-0.4652	0.819	No
Set 1 – Set 3:	-2.7987	0.183	No
Set 1 – Set 4:	-0.4539	0.825	No

Table 23 follows the same trends for pNN50 as all previous data. But it is noted that only NN50 and pNN50 follow the correct trends for delta B even when not statistically significant.

Table 24: Mean LF/HF Ratio

State 1 - State 2 (Delta A):	Delta Values	P Value	P < 0.05
Set 1:	1.4218	0.000	Yes
Set 2:	-0.0112	0.973	No
Set 3:	0.3930	0.173	No
Set 4:	0.5151	0.090	No
Delta Comparisons:			
Set 1 – Set 2:	-1.4329	0.004	Yes
Set 1 – Set 3:	-1.0287	0.018	Yes
Set 1 – Set 4:	-0.9067	0.038	Yes
State 2 – State 3 (Delta B):	**Delta Values**	**P Value**	**P < 0.05**
Set 1:	-0.3650	0.387	No
Set 2:	0.3908	0.354	No
Set 3:	0.7429	0.060	No
Set 4:	0.6358	0.106	No
Delta Comparisons:			
Set 1 – Set 2:	0.7559	0.217	No
Set 1 – Set 3:	1.1079	0.061	No
Set 1 – Set 4:	1.0008	0.089	No

The data for LF/HF ratio in Table 24 is the first data set in which the statistical significance is the exact opposite of what is required. Set comparisons in delta A being statistically significant show that State 1 and 2 were not always identical as they should be. The very high delta value for set 1 in delta A may be the cause.

Table 25: Mean HF Power

State 1 - State 2 (Delta A):	Delta Values	P Value	P < 0.05
Set 1:	-0.0011	0.000	Yes
Set 2:	-0.0008	0.000	Yes
Set 3:	-0.0007	0.000	Yes
Set 4:	-0.0006	0.002	Yes
Delta Comparisons:			
Set 1 – Set 2:	0.0002	0.252	No
Set 1 – Set 3:	0.0004	0.128	No
Set 1 – Set 4:	0.0005	0.037	Yes
State 2 – State 3 (Delta B):	**Delta Values**	**P Value**	**P < 0.05**
Set 1:	-0.0003	0.000	Yes
Set 2:	-0.0001	0.062	No
Set 3:	-0.0003	0.000	Yes
Set 4:	-0.0004	0.000	Yes
Delta Comparisons:			
Set 1 – Set 2:	0.0002	0.065	No
Set 1 – Set 3:	0.0001	0.975	No
Set 1 – Set 4:	-0.0001	0.623	No

Table 25 which evaluates the high frequency power of the vibration signal comes very close to showing the expected results. With the exception of the delta A set 1 – set 4 comparison being significant, and set 2 for delta B not being significant, the HF Power evaluation has come the closest to showing the physiological reactions that the researcher is expecting.

Table 26: Mean LF Power

State 1 - State 2 (Delta A):	Delta Values	P Value	P < 0.05
Set 1:	-0.0005	0.007	Yes
Set 2:	-0.0008	0.000	Yes
Set 3:	-0.0009	0.000	Yes
Set 4:	-0.0009	0.000	Yes
Delta Comparisons:			
Set 1 – Set 2:	-0.0003	0.302	No
Set 1 – Set 3:	-0.0004	0.177	No
Set 1 – Set 4:	-0.0004	0.118	No
State 2 – State 3 (Delta B):	**Delta Values**	**P Value**	**P < 0.05**
Set 1:	-0.0003	0.081	No
Set 2:	0.0001	0.451	No
Set 3:	0.0001	0.669	No
Set 4:	-0.0001	0.679	No
Delta Comparisons:			
Set 1 – Set 2:	0.0005	0.082	No
Set 1 – Set 3:	0.0004	0.134	No
Set 1 – Set 4:	0.0003	0.368	No

Table 26 for LF power behaves the same as all the time domain evaluations.

Table 27: Mean HRV Triangular Index

State 1 - State 2 (Delta A):	Delta Values	P Value	P < 0.05
Set 1:	-2.0845	0.001	Yes
Set 2:	-1.4843	0.016	Yes
Set 3:	-2.2623	0.001	Yes
Set 4:	-1.5836	0.017	Yes
Delta Comparisons:			
Set 1 – Set 2:	0.6001	0.487	No
Set 1 – Set 3:	-0.1778	0.840	No
Set 1 – Set 4:	0.5009	0.576	No
State 2 – State 3 (Delta B):	**Delta Values**	**P Value**	**P < 0.05**
Set 1:	-1.1486	0.010	Yes
Set 2:	-0.4269	0.337	No
Set 3:	-0.0336	0.942	No
Set 4:	-0.4370	0.327	No
Delta Comparisons:			
Set 1 – Set 2:	0.7216	0.247	No
Set 1 – Set 3:	1.1149	0.080	No
Set 1 – Set 4:	0.7116	0.254	No

The final physiological parameter evaluated in Table 27 shows the same trends as most other parameters.

5.5 Discussion

A statistical evaluation of all the HRV indicators shows very clearly, and with statistical significance, that there is indeed a measureable physiological reaction to vibration. Unfortunately this only applies for delta A, the change from state 1 to 2 where the participant is at rest before being exposed to vibration.

5.5.1 Analysis of Vibration

In order to better understand the changes in vibration the weighted RMS values for the vibrations were calculated using (ISO, 1997). Table 28 shows that the mean weighted RMS acceleration applied to the seat rail during state 2 was approximately 1.67m/s^2, and this means that delta A was approximately 1.67m/s^2 RMS as well. On the other hand, the delta B vibration change for set 4 was only approximately 0.43 m/s^2 RMS.

Table 28: RMS Acceleration Evaluations

Set:	Weighted RMS: State 2	Change in RMS State 2-3 (delta B):	Weighted RMS: State 3
Set 1	1.67 [m/s^2]	0.13 (7.78% Change)	1.80 [m/s^2]
Set 2	1.67 [m/s^2]	0.17 (10.2% Change)	1.84 [m/s^2]
Set 3	1.68 [m/s^2]	0.26 (15.5% Change)	1.94 [m/s^2]
Set 4	1.67 [m/s^2]	0.43 (25.7% Change)	2.10 [m/s^2]

With reference to Table 17, the RMS accelerations applied to the seat rail and the accelerations experienced by the test participants are not the same. This is a result of both the seat cushion transmissibility and the consideration of multiple axes for the overall ride values which are shown in Table 29.

Table 29: Overall Ride RMS Evaluations

Set:	Weighted RMS: State 2	Change in RMS State 2-3 (delta B):	Weighted RMS: State 3
Set 1	1.42 [m/s^2]	0.09 (6.34% Change)	1.51 [m/s^2]
Set 2	1.41 [m/s^2]	0.12 (8.51% Change)	1.53 [m/s^2]
Set 3	1.43 [m/s^2]	0.19 (13.3% Change)	1.62 [m/s^2]
Set 4	1.42 [m/s^2]	0.26 (18.3% Change)	1.68 [m/s^2]

A comparison between the intended vibrations in Table 28, and the vibrations which were experienced by the participants in Table 29, show the effects of the seats transmissibility. The changes required in weighted RMS according to Table 13 are still in line with the actual changes present. This is represented in Table 30. The differences between the signal change and the change on the seat rail can be attributed to the RMS signal applied to the actuator not being weighted. The signal measured from the seat rail does have frequency weighting. The overall ride change matches the change in the original signal more closely. Since the expected and actual delta values are so similar, this is not considered to be the cause for so many statistically insignificant results.

Table 30: Summary of RMS Vibration Changes for delta B

Set:	Signal RMS Change:	Change on Seat Rail:	Change in overall Ride:
Set 1	6.47%	7.78%	6.34%
Set 2	9.57%	10.2%	8.51%
Set 3	14.6%	15.5%	13.3%
Set 4	22.0%	25.7%	18.3%

5.5.2 Analysis of Physiological responses

The physiological responses measured can be split into 3 broad categories as shown in Table 5 that all had similar results. The first of these to be discussed are the frequency based evaluations.

LF/HF Ratio:

The LF/HF ratio increases with physiological stress, and this was true for most responses measured for both delta A and B. Unfortunately the mean reaction for set 2 during delta A, and set 1 for delta B both showed decreasing values. These two outliers contradict the expectation that physiological stress increases with WBV.

The delta comparisons between delta B values show the expected trends, but none are statistically significant. On the other hand, comparisons between the delta A values contradict expectations since delta A values should be approximately equal. This can be dismissed by noting that the mean delta A for set 1 is exceptionally high, affecting comparisons. The mean was calculated excluding outliers, so the reason for this large value is not known. In conclusion, with the exception of the large delta A skewing data, the recorded LF/HF values do show the expected trends, but no changes

are statistically significant. As a result, the LF/HF ratio is not considered a suitable indicator of physiological stress due to WBV with too many discrepancies.

HF Power:

The HF power of R-R intervals represent parasympathetic activity in the ANS in controlled conditions. It is expected that HF power will decrease with increased breathing rate and physiological stress. This study showed a good correlation to these expectations, with statistically significant decreases for delta A, as well as B. Set 2 did decrease during delta B, but not enough to be significant.

Comparisons between delta values for delta A are not significant, except when comparing set 1 to set 4. Comparisons for delta B values are all insignificant, implying that the level of stress did not fluctuate for different changes in vibration. This is an interesting observation. Overall with the exception of two discrepancies and unexpected delta B comparison results HF power is considered a potential indicator of WBV.

LF Power:

LF power is similar to HF power as it decreases with physiological stress, but represents a combination of Parasympathetic and Sympathetic nervous system activity. This contributes to the unreliability of the LF/HF ratio. During this study the LF power evaluations showed perfect results in line with the expected stress reactions for delta A. Unfortunately there are no statistically significant results for delta B.

The frequency based analysis for physiological stress as a result of WBV did yield reliable results for delta B, and only two of the three indicators could be used for delta A. Of all three indicators the researcher finds that HF and LF power are the most promising cardiovascular indicators of WBV. The next evaluations to be considered are time domain evaluations.

RR intervals, Mean and SD:

The Mean RR intervals are expected to decrease with physiological stress as HR increases. As with LF power evaluations, the indicator has the expected response when evaluating delta A, but no significant results are recorded for delta B. The Standard Deviation in the RR intervals is also expected to decrease as HRV decreases. This indicator has the same results as mean RR.

Neither of the two indicators showed statistically significant changes for any of the delta B cases, but did show perfect results for all cases of delta A.

RMSSD:

With the exception of set 4 during delta A, RMSSD also shows the expected results with statistical significance. As with RR evaluations, the data is not statistically significant for any delta B values, and when comparing delta B values only a comparison between set 1 and 4 showed statistically significant changes. As a result, RR evaluations are considered superior to RMSSD calculations for WBV evaluation.

NN50 and pNN50:

pNN50 and NN50 values show the expected trends in all cases, but are only consistently significant for delta A evaluations. This makes them one of the most reliable time domain indicators of stress due to WBV. The indicators are the first to have all expected trends, but lacking significance.

Considering all indicators thus far fail during delta B, both are considered reliable in determining physiological stress as a result of WBV.

Mean HR and BR:

Since HR and BR are both considered complimentary measurements and were not the focus of this research, they were not statistically evaluated. BR has shown very promising trends during this research and warrants a more in depth analysis. It is possible that BR is affected by the mechanical shocks from vibration preventing normal breathing or otherwise forcing an increased breathing rate.

After evaluating time domain methods, NN50 and pNN50 are identified as the most reliable indicators of physiological stress during WBV. The final indicator to be considered is a geometric indicator.

HRV Triangular Index:

The triangular index performs similarly to RMSSD, having perfect results for delta A, but no significance for delta B. As a result this indicator cannot be recommended.

5.5.3 Summary

In summary, the vibrations applied to the participants were very similar to the intended vibrations. Although different they should not affect the comparisons between these vibration signals since the differences (X and Y vibrations, seat cushion etc.) are constant for all vibration sets.

The physiological stress indicators that performed the best are LF and HF power for frequency analysis and pNN50 and NN50 for time domain analysis. The researcher finds pNN50 and NN50 evaluations to have the closest results to what was expected.

Chapter 6: Conclusion and Future Work

This is the final chapter of the dissertation, concluding all work done and summarising all findings and experimental results.

6.1 Research Conclusion

After evaluating the ECG data collected it was determined that although the body does consistently react to vibrations, this research was unable to find any correlation between the amplitude of vibrations experienced and changes in physiological parameters. This is shown by many HRV indicators behaving as expected for delta A, but not to delta B.

The researcher can conclude that there is indeed a physiological response to vibration, but more work is required in order to fully quantify this response. The pNN50 and NN50 indicators can reliably be used to identify when a participant is exposed to vibration from rest. No indicators were able to reliably identify a change in vibration once a participant was subjected to an initial vibration.

This may be due to the indicators not being sensitive enough to identify increases in physiological stress once a significant amount of stress is already present.

6.2 Recommendations

Recommendations for future work would be to repeat the same type of tests, but with more signal variations and therefore more people. The larger sample sizes will help to further mitigate biodynamic variability and having more than only 4 vibration sets will help establish statistically significant trends for vibration signal amplitude change vs physiological response. In this experiment there were 4 vibration sets consisting of 15 participants each.

A statistician should be consulted to determine the minimum amount of signal variations which would be required. These variations would ideally spread across weighted RMS values from 0.1 to 1 m/s^2 in order to ensure that the signals are more representative of driving conditions. A range from 0.1 to 1 will also ensure a larger % change in the weighted RMS. The larger differences would help to determine how large a change in vibration should be for HRV indicators to reliably react. Future work should also report back on effect size and the confidence intervals thereof rather than rely solely on null hypothesis testing. Improvements in statistical analysis and more sophisticated evaluation methods may yield better results.

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Appendix A: Ethical Clearance

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Engineering,
Built Environment and Information Technology

1956 – 2016
60
years of
Engineering Education

Reference number: EBIT/71/2016

4 November 2016

Mr JS Jooste
Department Mechanical and Aeronautical Engineering
University of Pretoria
Pretoria
0028

Dear Mr Jooste,

FACULTY COMMITTEE FOR RESEARCH ETHICS AND INTEGRITY

Your recent application to the EBIT Research Ethics Committee refers.

Approval is granted for the application with reference number that appears above.

1. This means that the research project entitled "Biofeedback in ride comfort evaluation" has been approved as submitted. It is important to note what approval implies. This is expanded on in the points that follow.
2. This approval does not imply that the researcher, student or lecturer is relieved of any accountability in terms of the Code of Ethics for Scholarly Activities of the University of Pretoria, or the Policy and Procedures for Responsible Research of the University of Pretoria. These documents are available on the website of the EBIT Research Ethics Committee.
3. If action is taken beyond the approved application, approval is withdrawn automatically.
4. According to the regulations, any relevant problem arising from the study or research methodology as well as any amendments or changes, must be brought to the attention of the EBIT Research Ethics Office.
5. The Committee must be notified on completion of the project.

The Committee wishes you every success with the research project.

Prof JJ Hanekom
Chair: Faculty Committee for Research Ethics and Integrity
FACULTY OF ENGINEERING, BUILT ENVIRONMENT AND INFORMATION TECHNOLOGY

Fakulteit Ingenieurswese, Bou-omgewing en Inligtingtegnologie
Lefapha la Boetšenere, Tikologo ya Kago le Theknolotši ya Tshedimošo

The Research Ethics Committee, Faculty Health Sciences, University of Pretoria complies with ICH-GCP guidelines and has US Federal wide Assurance.
- FWA 00002567, Approved dd 22 May 2002 and Expires 03/20/2022.
- IRB 0000 2235 IORG0001762 Approved dd 22/04/2014 and Expires 03/14/2020.

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Health Sciences Research Ethics Committee

28/04/2017

Approval Certificate
New Application

Ethics Reference No.: EBIT/71/2016

Title: Biofeedback in Ride Comfort Evaluation

Dear Mr Jacques Jooste

The **New Application** as supported by documents specified in your cover letter dated 20/04/2017 for your research received on the 20/04/2017, was approved by the Faculty of Health Sciences Research Ethics Committee on its quorate meeting of 26/04/2017.

Please note the following about your ethics approval:
- Ethics Approval is valid for 1 year
- Please remember to use your protocol number (**EBIT/71/2016**) on any documents or correspondence with the Research Ethics Committee regarding your research.
- Please note that the Research Ethics Committee may ask further questions, seek additional information, require further modification, or monitor the conduct of your research.

Ethics approval is subject to the following:
- The ethics approval is conditional on the receipt of **6 monthly written Progress Reports**, and
- The ethics approval is conditional on the research being conducted as stipulated by the details of all documents submitted to the Committee. In the event that a further need arises to change who the investigators are, the methods or any other aspect, such changes must be submitted as an Amendment for approval by the Committee.

We wish you the best with your research.

Yours sincerely

Dr R Sommers; MBChB; MMed (Int); MPharMed,PhD
Deputy Chairperson of the Faculty of Health Sciences Research Ethics Committee, University of Pretoria

The Faculty of Health Sciences Research Ethics Committee complies with the SA National Act 61 of 2003 as it pertains to health research and the United States Code of Federal Regulations Title 45 and 46. This committee abides by the ethical norms and principles for research, established by the Declaration of Helsinki, the South African Medical Research Council Guidelines as well as the Guidelines for Ethical Research: Principles Structures and Processes, Second Edition 2015 (Department of Health).

☎ 012 356 3084 deepeka.behari@up.ac.za / fhsethics@up.ac.za http://www.up.ac.za/healthethics
✉ Private Bag X323, Arcadia, 0007 - Tswelopele Building, Level 4, Room 60, Gezina, Pretoria

Appendix B: SOP

1: Pre start-up Checks

- All accelerometers still correctly positioned.
- No loose mechanical connections on testing platform.
- No loose wires.
- All wires correctly routed to prevent tripping.

2: Start-up Procedure

- Ensure hydraulic power pack and cooling tower are switched on.
- Turn on actuator leak pump.
- Turn on Cubis control module and start up software interface.
- Turn on high pressure to actuator.
- Set actuator displacement to 0mm. (Home position)
- Activate displacement and acceleration limits.
- Trial vibration signal played through actuator to check limit switches function.

3: Safety Requirements

- Always check limit switches are engaged before each test.
- Actuator must be in home position before a participant climbs onto seat.
- Participant must have emergency stop switch.
- Before any signal is played participant must be secured in seat via safety belt.
- Observer must have view of participant during testing.

4: Experimental procedure

- Participant enters lab area and is briefed.
- Participant is assisted in wearing relevant physiological sensors.
- Participant is lead to the testing platform and secured in the seat.
    - Commence baseline measurement.
- Participant is informed via a visual que that vibrations will start
    - Commence reference-alternative vibration test.
- Participant is assisted in climbing off testing platform and removing physiological sensors.
- Next participant enters.

5: In case of emergency stop

- Participant is assisted in climbing off testing platform and given a seat to rest/wait.
- All safety and pre start-up checks are repeated.
- Test may be repeated.

Appendix C: Informed Consent Forms

Informed consent form

Title of research project: Physiological Responses to Whole Body Vibration (Pilot Study)

Introduction:

You are invited to partake in a research study. The information provided in this form will assist you in deciding if you would like to participate. Before you decide to partake in the study it is important that you understand how the tests will be conducted and what will be expected of you. If you have any questions or feel that anything has not been fully explained, do not hesitate to ask the investigator. Your health is important. Please do not participate in this study should you have any medical condition that deems you unfit for such activities.

Purpose of the study:

The purpose of this study is to determine which physiological responses can be used to indicate the perception of ride by a human. By determining which, if any, physiological responses can be used to reliably measure ride comfort, advances can be made in vehicle dynamics and vehicle control.

Explanation of the procedure to be followed:

You will be required to sit on a vehicle seat which has been mounted to a hydraulic actuator. This actuator will move the seat in order to simulate the driving conditions you would expect from a tar and rural road. As you sit in the seat sensors will be used to record your physiological responses to different vibrations. The tests will be performed over a period of 5 days and will consist of two 2min signals played to you one after the other, after which you may leave and return to be tested again the next day. At any stage you are allowed to indicate if you do not want to continue participating in the tests.

The sensors that will be used will measure Heart Rate (HR), Heart Rate Variability (HRV), and an Electroencephalogram (EEG, Brain activity). The sensors measuring the physiological parameters that you will be wearing measure electrical impulses from your muscles and/or brain. The sensors are non-invasive and consist of electrodes being placed on your skin. The electrode is placed on the skin by an adhesive sticker, and poses no risk of electrical shock.

Risks involved:

The risks involved are similar to the risks associated with driving a vehicle on a secondary gravel road. All testing equipment adheres to the safety standards in ISO 13090-1. The tests will be conducted at the University of Pretoria in a controlled environment.

Exclusion:

Before participating in the experiment you are required to attend a Pre-Screening test. This test will be done by Dr CC Grant, the screening will be used to ensure that no test participants have pulmonary, metabolic or orthopaedic diseases. For your own safety, you are required to inform Dr Grant if you have a history of cardiovascular, hepatic or respiratory impairment.

Any of the following will exclude you from the study:

- Active disease of respiratory system
- Active disease of genito-urinary system
- Active disease of the cardiovascular system
- Active disease or defect of the musculo-skeletal system
- Active chronic disease or disorder of the nervous system
- Pregnancy
- Mental health
- Recent trauma and surgical procedures
- Smoking
- Use of any medication
- Prosthesis

We require male participants between the ages of 23 and 30

Benefits of the study:

You will be making a contribution to the development of more comfortable vehicles as well as to the understanding of the human body and its perception to vibration and other factors.

Has this study received ethical approval?

Yes, this study has been approved by the Ethics Committee of the Faculty of Engineering, Build Environment and IT, as well as the Faculty of Health Sciences of the University of Pretoria.

Confidentiality:

All information submitted on the questionnaires will be regarded as confidential. The results obtained from the questionnaires as well as the measurements taken on the vehicle will be published in such a fashion that participants remain unidentifiable.

Contact details:

If any further questions comes to mind or if there are any concerns after you have partaken in the study please contact Jacques Jooste on 072 600 8265 or send an email at jacquessjooste@gmail.com.

Consent to participate in this study:

1 I …… hereby voluntarily grant my permission for participation in the project as explained to me by

……

2 The nature, objective, possible safety and health implications have been explained to me and I understand them.

3 I understand my right to choose whether to participate in the project and that the information furnished will be handled confidentially. I am aware that the results of the investigation may be used for the purposes of publication.

4 Upon signature of this form, you will be provided with a copy.

Signed: _____ Date: _____

Witness: _____ Date: _____

Researcher: _____ Date: _____

Informed consent form

Title of research project: Physiological Responses to Whole Body Vibration (Main Study)

Introduction:

You are invited to partake in a research study. The information provided in this form will assist you in deciding if you would like to participate. Before you decide to partake in the study it is important that you understand how the tests will be conducted and what will be expected of you. If you have any questions or feel that anything has not been fully explained, do not hesitate to ask the investigator. Your health is important. Please do not participate in this study should you have any medical condition that deems you unfit for such activities.

Purpose of the study:

The purpose of this study is to determine which physiological responses can be used to indicate the perception of ride by a human. By determining which, if any, physiological responses can be used to reliably measure ride comfort, advances can be made in vehicle dynamics and vehicle control.

Explanation of the procedure to be followed:

You will be required to sit on a vehicle seat which has been mounted to a hydraulic actuator. This actuator will move the seat in order to simulate the driving conditions you would expect from a tar and rural road. As you sit in the seat sensors will be used to record your physiological responses to different vibrations. The tests will be performed on a day of your choosing and will consist of a 5min signal played to you with a pause in the middle, after which you may leave. At any stage you are allowed to indicate if you do not want to continue participating in the tests.

The sensors that will be used will measure Heart Rate (HR), Heart Rate Variability (HRV), and an Electroencephalogram (EEG, Brain activity). The sensors measuring the physiological parameters that you will be wearing measure electrical impulses from your muscles and/or brain. The sensors are non-invasive and consist of electrodes being placed on your skin. The electrode is placed on the skin by an adhesive sticker, and poses no risk of electrical shock.

Risks involved:

The risks involved are similar to the risks associated with driving a vehicle on a secondary gravel road. All testing equipment adheres to the safety standards in ISO 13090-1. The tests will be conducted at the University of Pretoria in a controlled environment.

Exclusion:

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Any of the following will exclude you from the study:

- Active disease of respiratory system
- Active disease of genito-urinary system
- Active disease of the cardiovascular system
- Active disease or defect of the musculo-skeletal system
- Active chronic disease or disorder of the nervous system
- Pregnancy
- Mental health
- Recent trauma and surgical procedures
- Smoking
- Use of any medication
- Prosthesis

We require male participants between the ages of 20 and 27

Benefits of the study:

You will be making a contribution to the development of more comfortable vehicles as well as to the understanding of the human body and its perception to vibration and other factors.

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Yes, this study has been approved by the Ethics Committee of the Faculty of Engineering, Build Environment and IT, as well as the Faculty of Health Sciences of the University of Pretoria.

Confidentiality:

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Contact details:

If any further questions comes to mind or if there are any concerns after you have partaken in the study please contact Jacques Jooste on 072 600 8265 or send an email at jacquessjooste@gmail.com.

Consent to participate in this study:

1 I …… hereby voluntarily grant my permission for participation in the project as explained to me by

……

2 The nature, objective, possible safety and health implications have been explained to me and I understand them.

3 I understand my right to choose whether to participate in the project and that the information furnished will be handled confidentially. I am aware that the results of the investigation may be used for the purposes of publication.

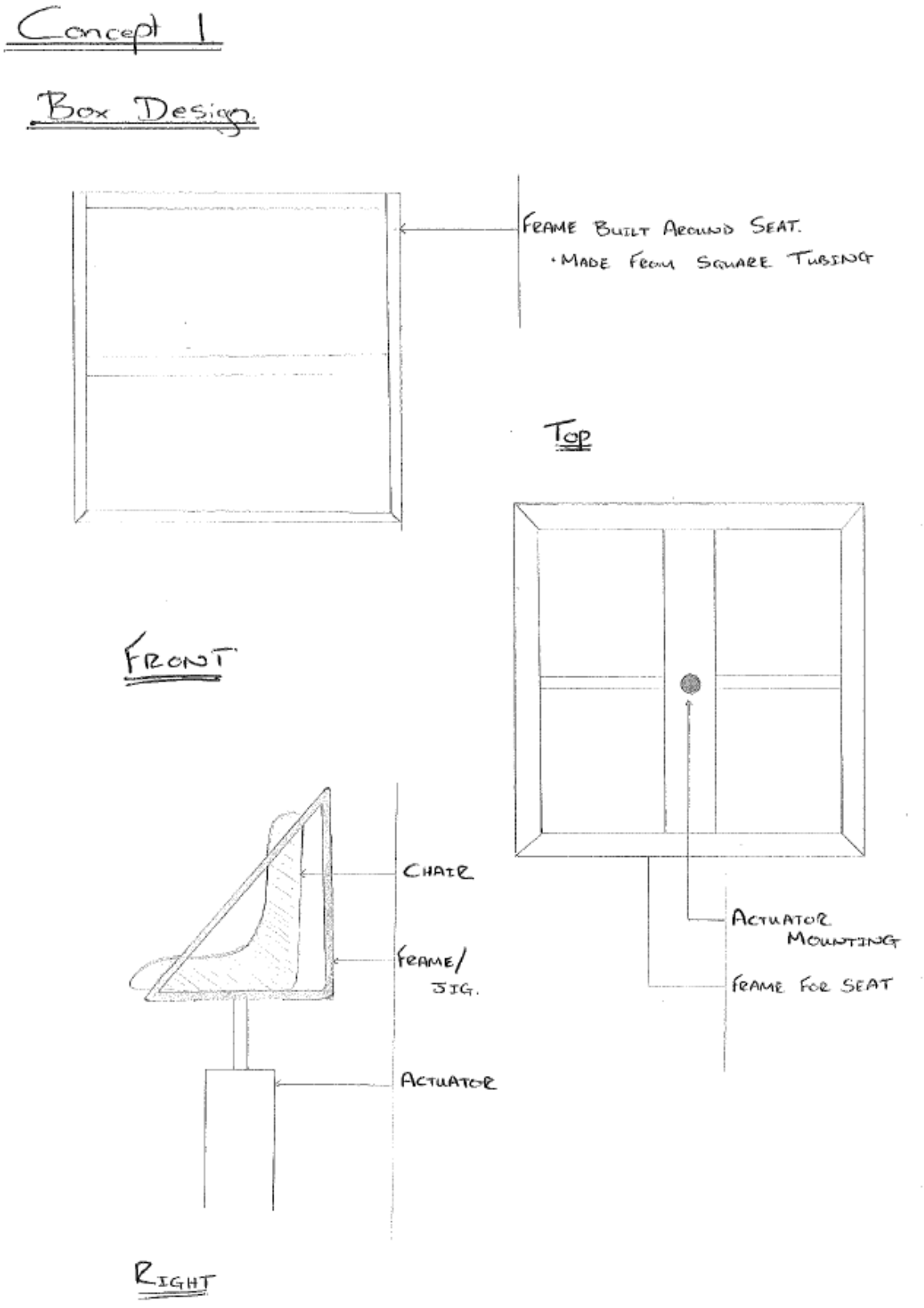
4 Upon signature of this form, you will be provided with a copy.

Signed: _____ Date: _____

Witness: _____ Date: _____

Researcher: _____ Date: _____

Appendix D: Interface Concepts

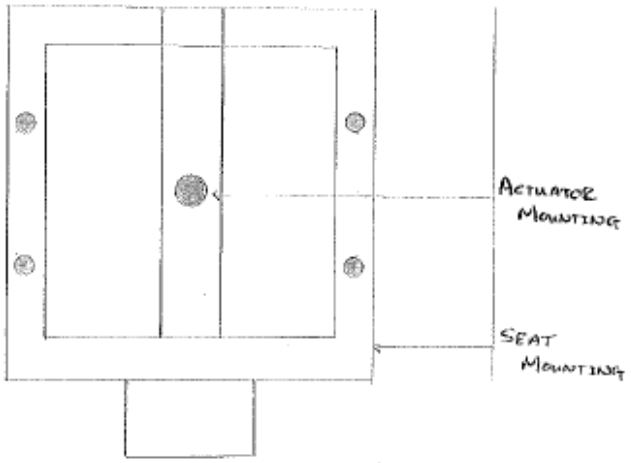


Concept 2

Rib Design

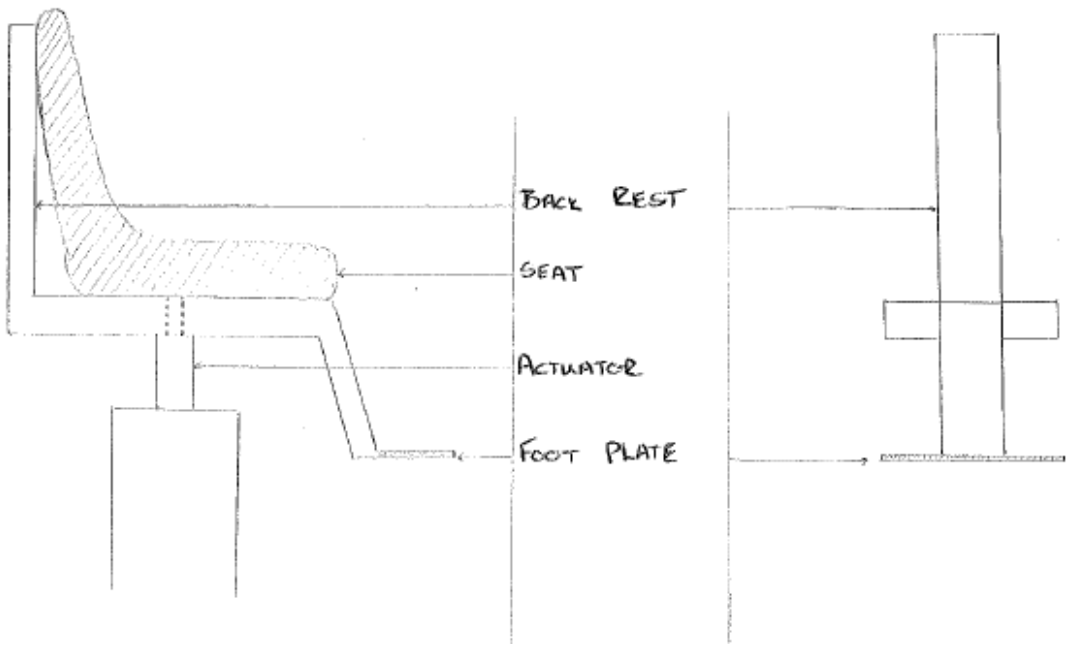
Everything would be mounted onto a single sturdy rib.

Top.



Front

Side

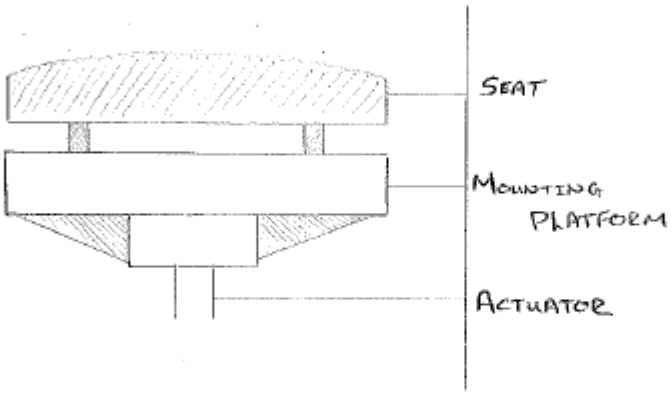


Concept 3

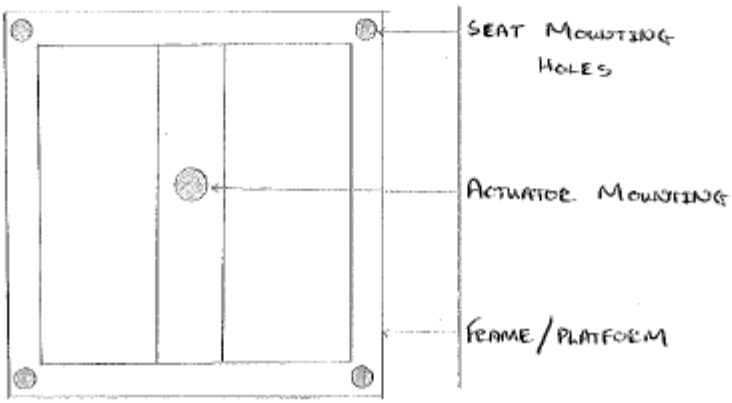
Simple Interface

Very Simple Interface, Basic absorbtion plate between actuator and the seat

Front

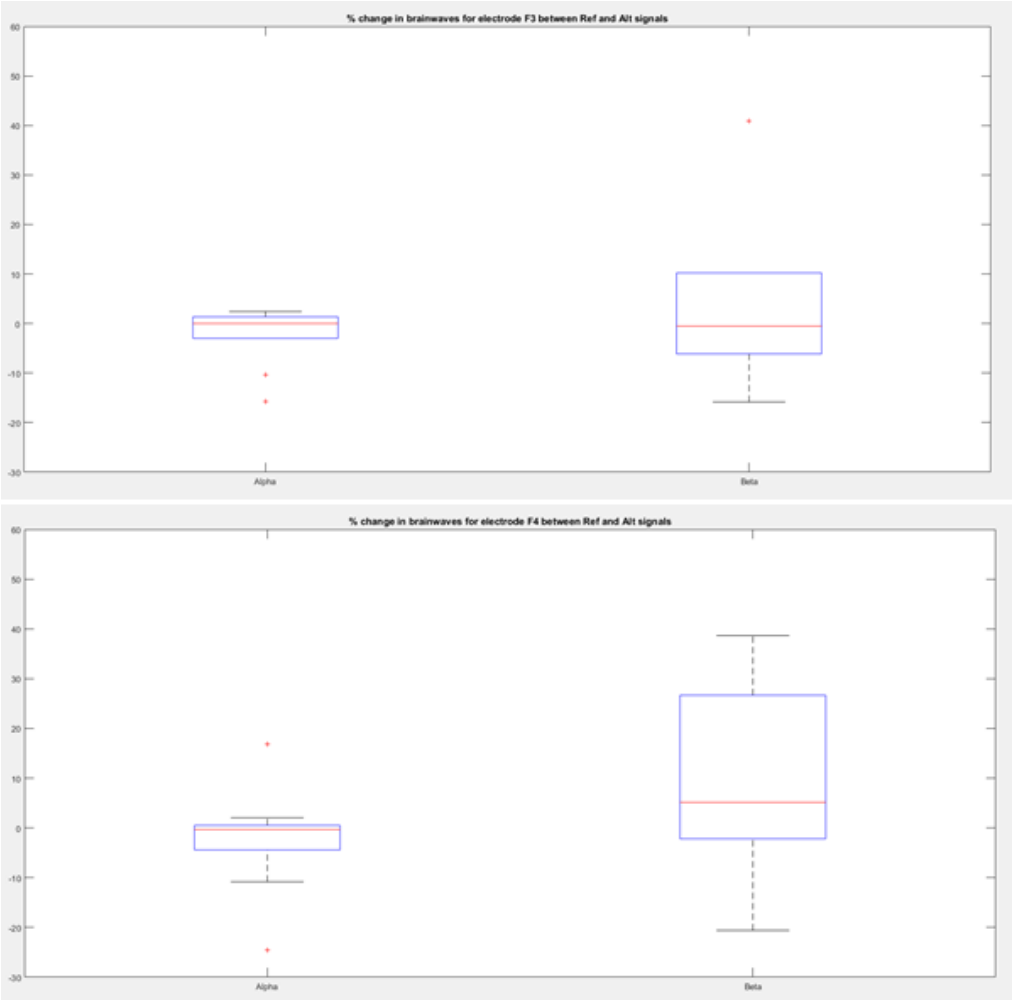


Top



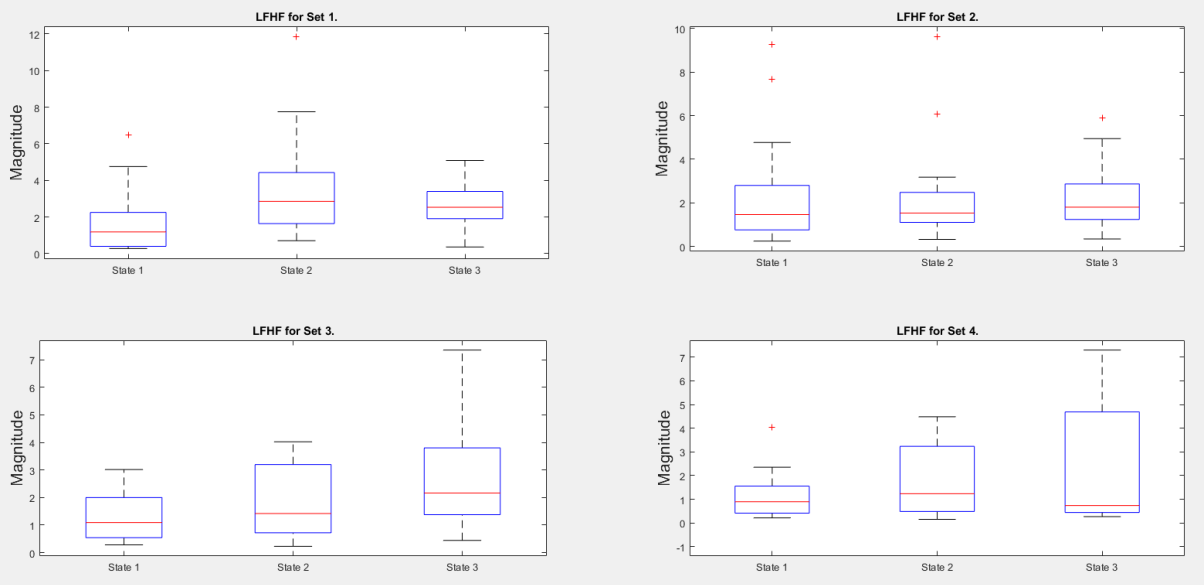
Appendix E: EEG Data

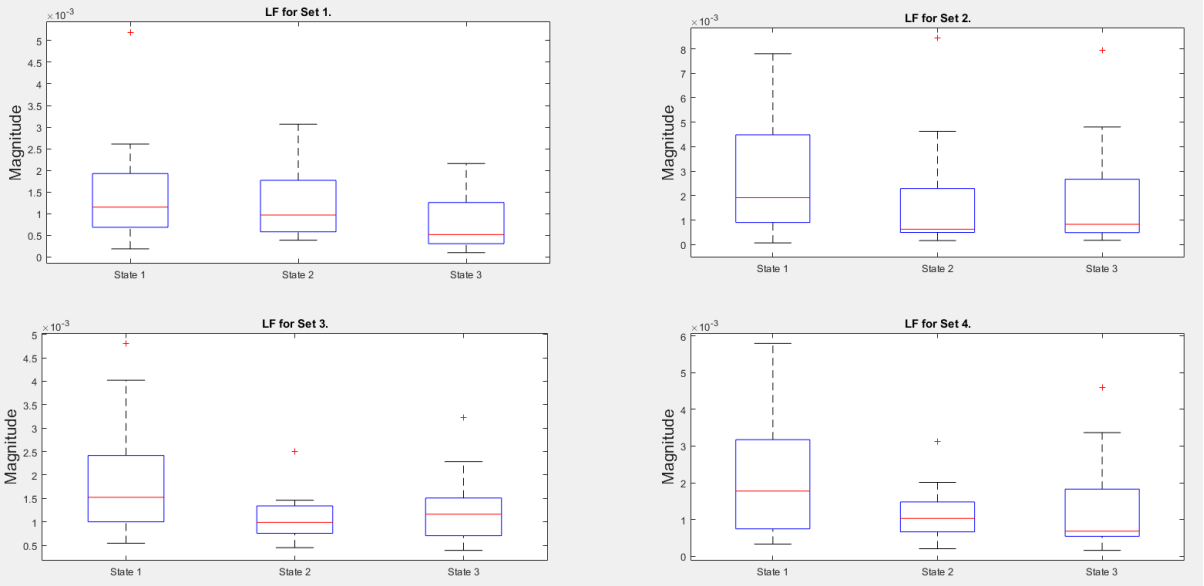
As mentioned in Section 3.4.2, some EEG data was collected from the test participants before the EEG equipment was no longer available. As a result of equipment availability limitations, EEG measurements were not included in the main study, but are believed to be effective in evaluating physiological stress. All EEG data processing was done in Matlab, the measured signals from the electrodes were filtered into two separate frequency bands and the RMS values of the new signals were used as an indication of specific brainwaves. (Yu-Kuang and Hwang, 2011) had great success with electrodes in the cranial positions F3 and F4, and found that beta waves rise as WBV increases. The figure shows how beta waves for the 10 participants changed much more than the alpha waves from the reference to alternative signals, confirming the observations made by (Yu-Kuang and Hwang, 2011). It should be noted that this data includes only 10 participants over one day of pilot testing, because the data is incomplete and the sample size small it was excluded from the main report.

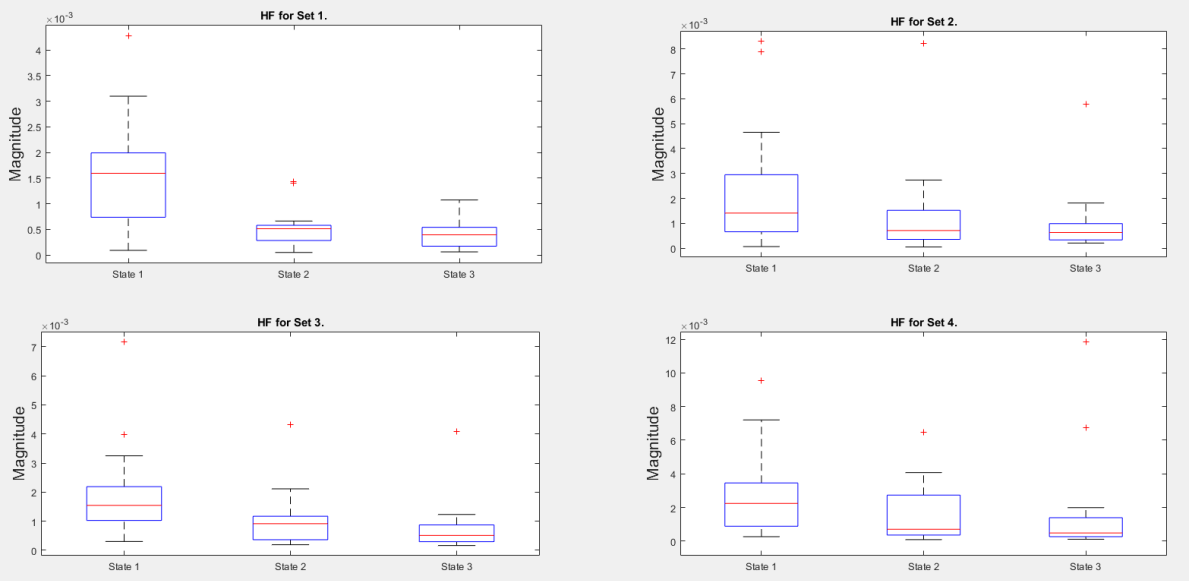


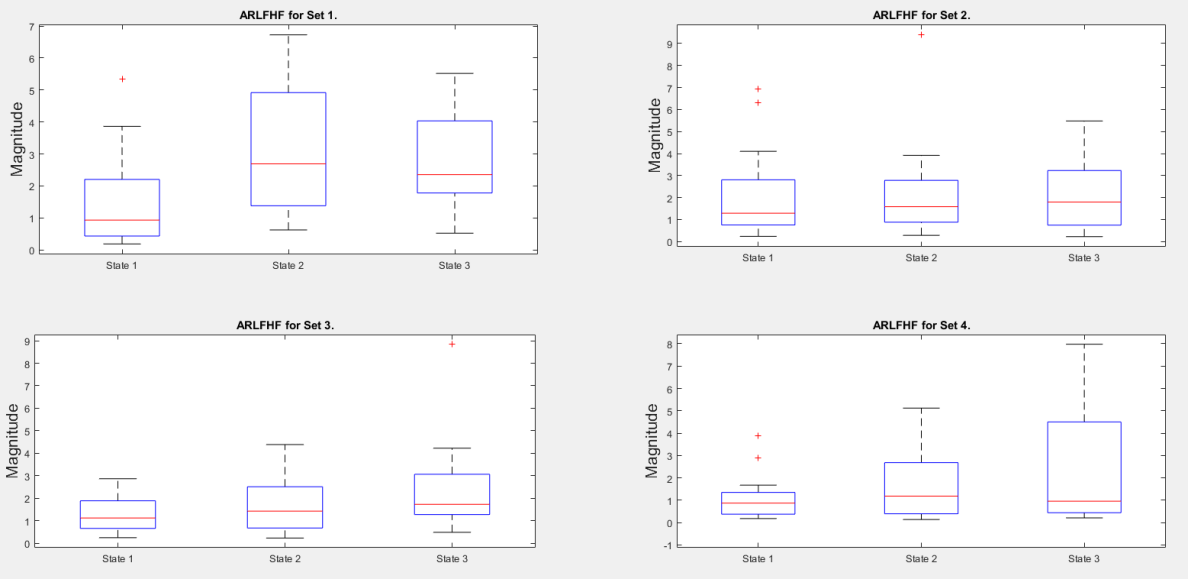
	% Change in Alpha waves	% Change in Beta waves
Electrode F3	0	-0.5
Electrode F4	-0.32	5.2
Average Change	-0.16	2.35

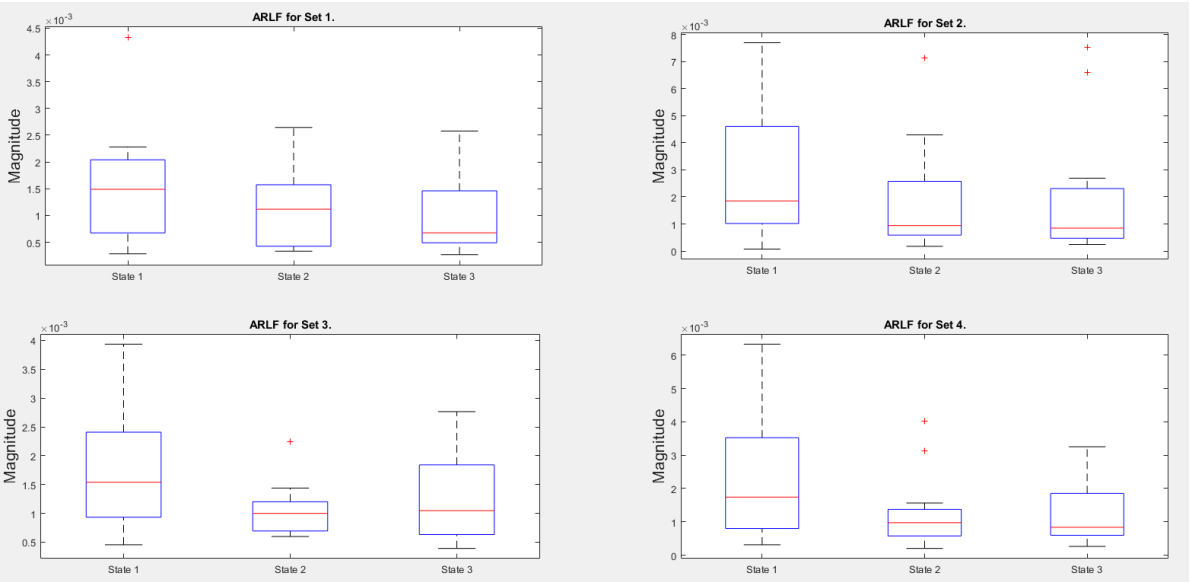
Appendix F: HRV Indicators

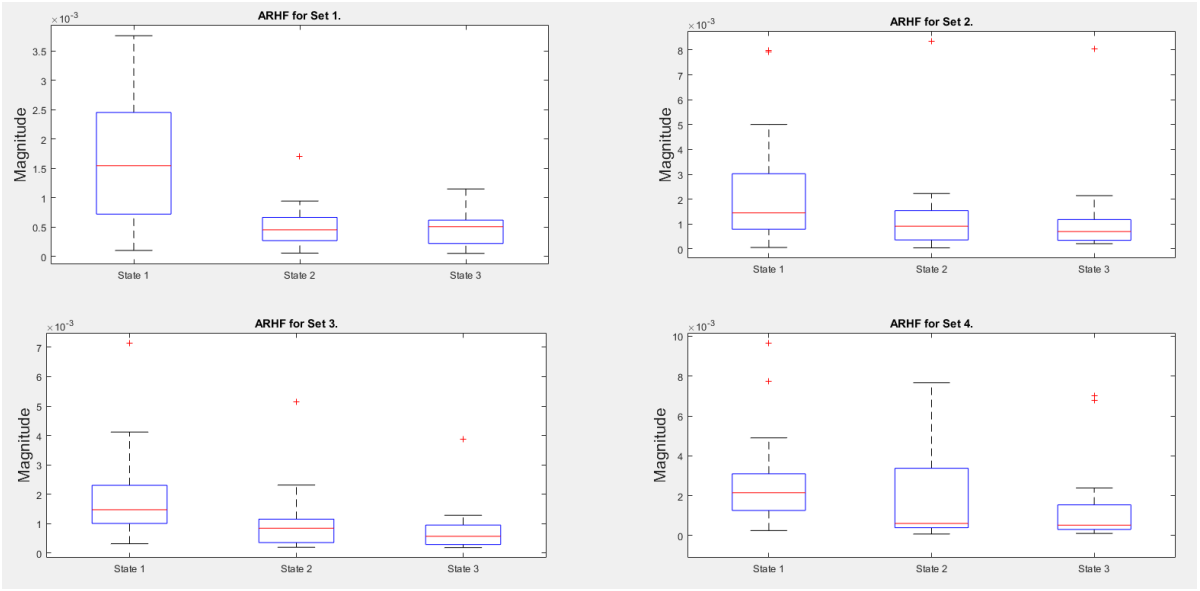


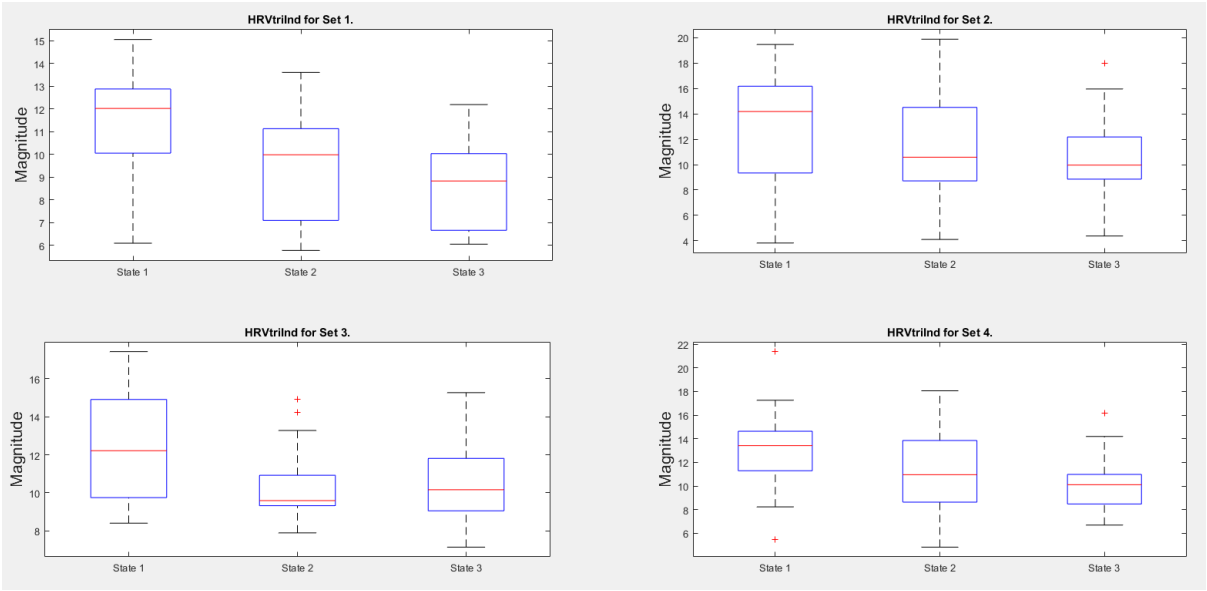


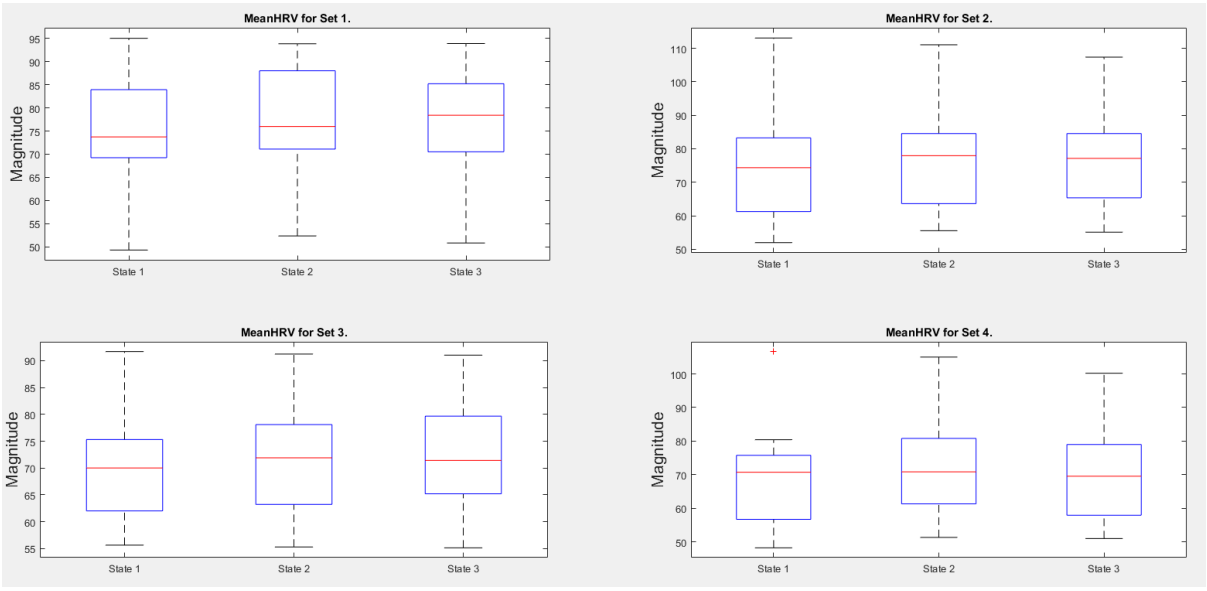

HF for Set 1.
HF for Set 2.
HF for Set 3.
HF for Set 4.
Magnitude
State 1
State 2
State 3

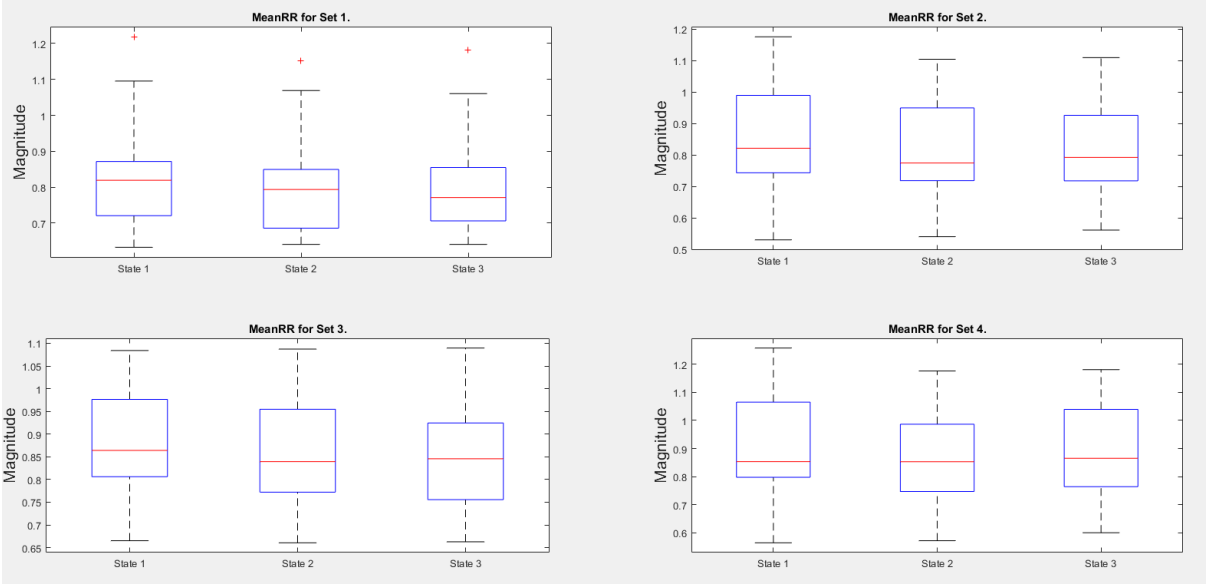

ARLFHF for Set 1.
ARLFHF for Set 2.
ARLFHF for Set 3.
ARLFHF for Set 4.
Magnitude
State 1
State 2
State 3

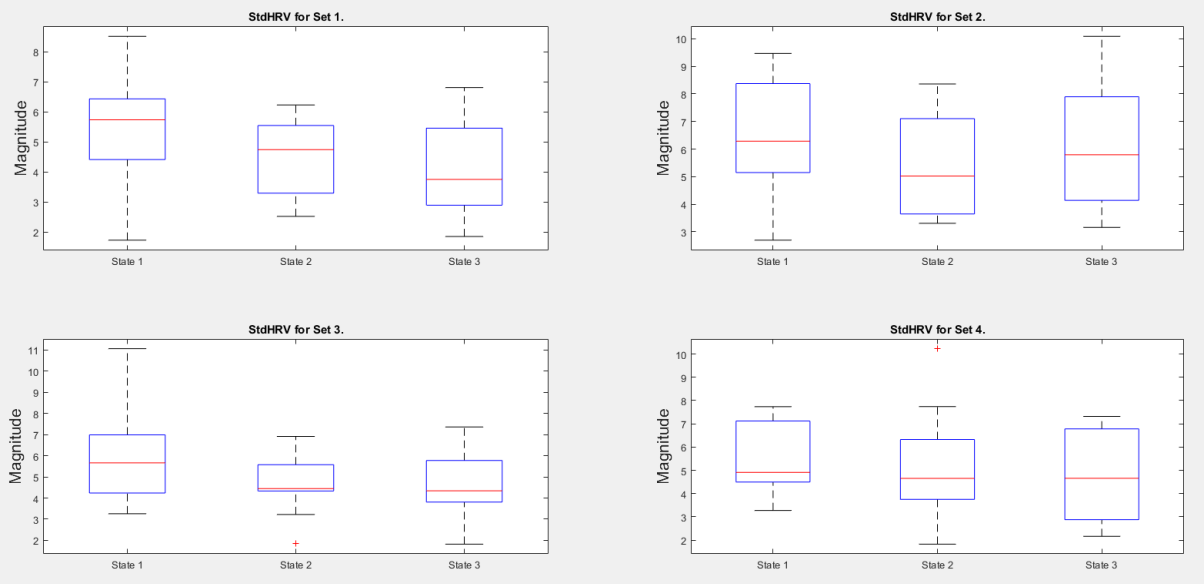

ARLF for Set 1.
ARLF for Set 2.
ARLF for Set 3.
ARLF for Set 4.
Magnitude
State 1
State 2
State 3

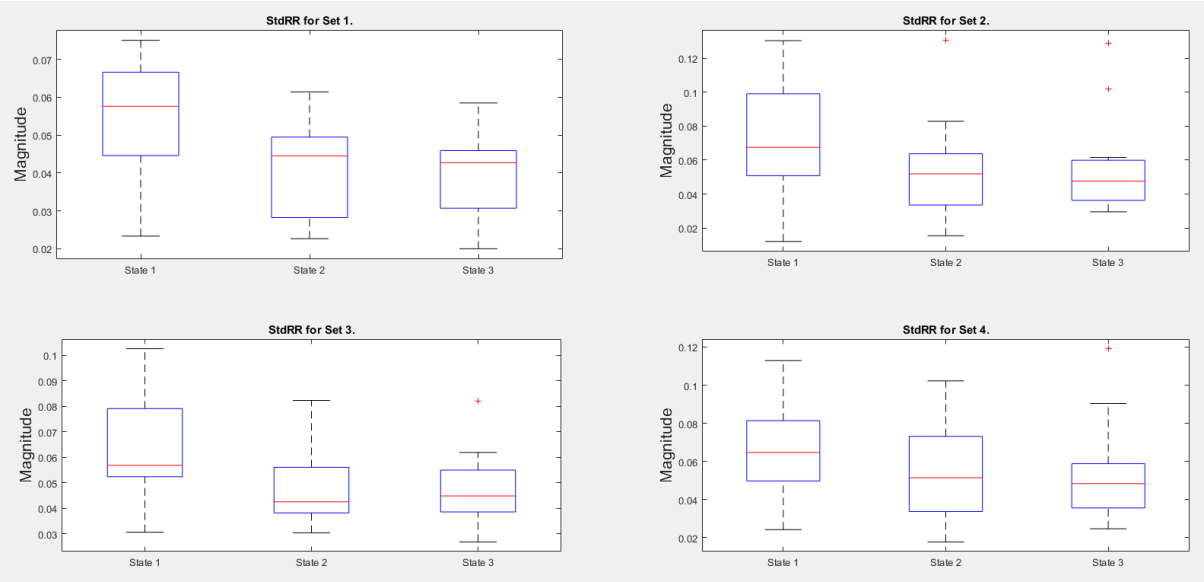

ARHF for Set 1.
ARHF for Set 2.
ARHF for Set 3.
ARHF for Set 4.
Magnitude
State 1
State 2
State 3

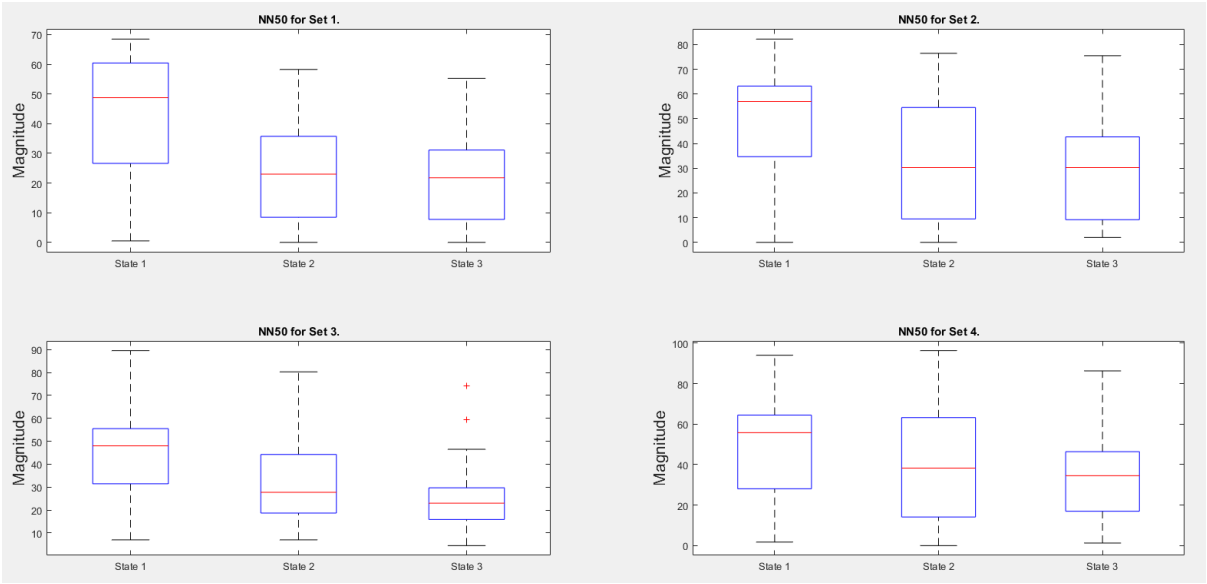

HRVtrilnd for Set 1.
HRVtrilnd for Set 2.
HRVtrilnd for Set 3.
HRVtrilnd for Set 4.
Magnitude
State 1
State 2
State 3

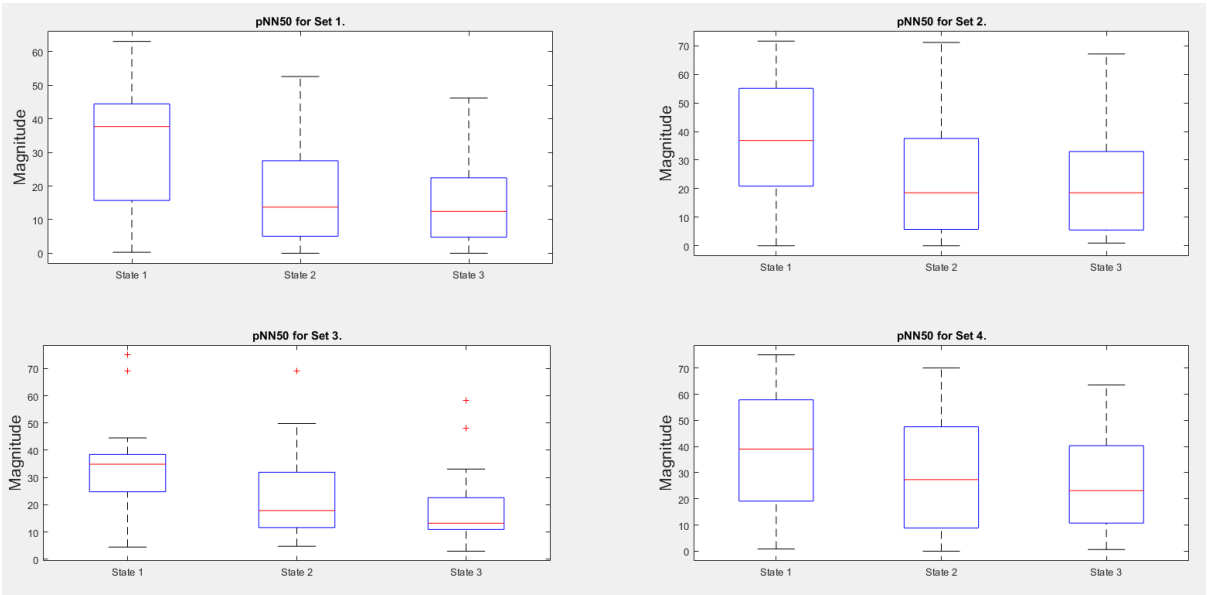

MeanHRV for Set 1.
MeanHRV for Set 2.
MeanHRV for Set 3.
MeanHRV for Set 4.
Magnitude
State 1
State 2
State 3

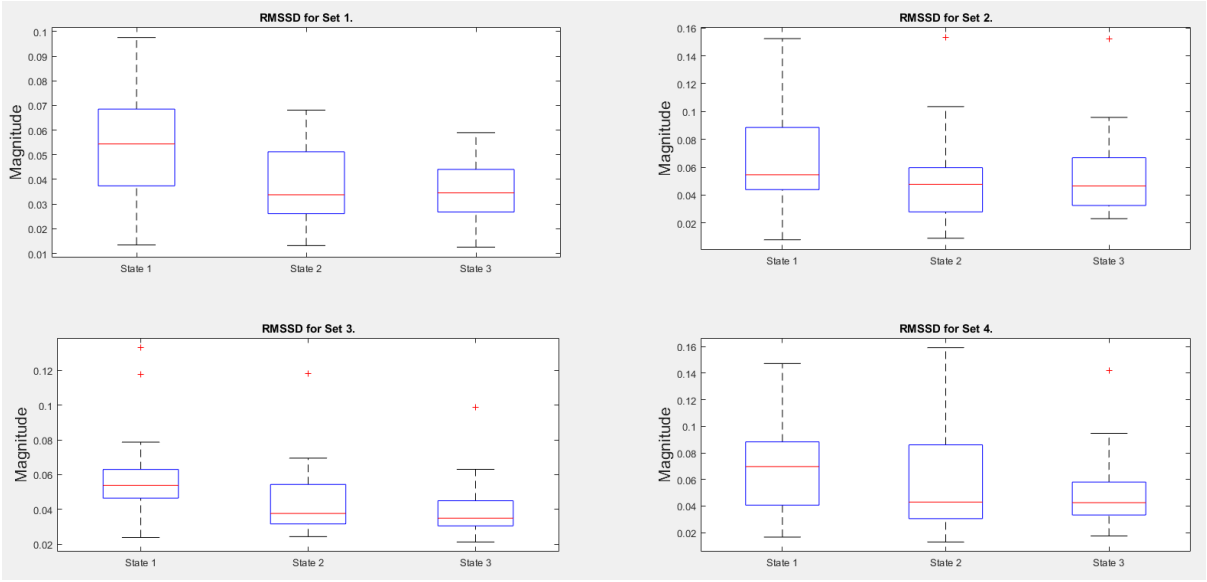

MeanRR for Set 1.
MeanRR for Set 2.
MeanRR for Set 3.
MeanRR for Set 4.
Magnitude
State 1
State 2
State 3


StdHRV for Set 1.
StdHRV for Set 2.
StdHRV for Set 3.
StdHRV for Set 4.
Magnitude
State 1
State 2
State 3


StdRR for Set 1.
StdRR for Set 2.
StdRR for Set 3.
StdRR for Set 4.
Magnitude
State 1
State 2
State 3


NN50 for Set 1.
NN50 for Set 2.
NN50 for Set 3.
NN50 for Set 4.
Magnitude
State 1
State 2
State 3


pNN50 for Set 1.
pNN50 for Set 2.
pNN50 for Set 3.
pNN50 for Set 4.
Magnitude
State 1
State 2
State 3


RMSSD for Set 1.
RMSSD for Set 2.
RMSSD for Set 3.
RMSSD for Set 4.
Magnitude
State 1
State 2
State 3