University of Southern Queensland

Faculty of Health, Engineering and Sciences

Vibration Analysis of an Excavator to Investigate the Effects on the Operator

A dissertation submitted by

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Abstract

Health and safety are a major consideration for all engineering projects, and it is the engineer's responsibility to ensure designs meet adequate health and safety requirements. If an engineering design is not safe, it can put the lives of the community or an individual at risk. This project aims to investigate this idea in relation to the operation of a 24-tonne excavator and the possible effects that the operator may experience due to exposure to whole body vibration. Several firsthand accounts and a survey of 410 machine operators in a previous study by Chris L Zimmerman highlighted that lower back pain is highly common between machine operators and thus posed the questions, what is causing this pain? Are the vibration controls in place sufficient? Past research has provided vibrational data and information for mining machinery and the causes of vibration; however, it was evident that this data was quite limited for excavators and so this gap in knowledge was the origin for the focus of this project. Research was conducted to gain a strong understanding of vibration and how to effectively measure it and analyse it, with a focus on its effects on the human body. Vibrational data was collected from an excavator during general operation using an Arduino and MPU6050 accelerometer which collected acceleration data in the X, Y, and Z axes. The data that was collected was able to be modified to produce the vibrational data present during operation, this data was used to create vibration graphs for each axis. Computational simulations were conducted using the experimental data collected to model and observe the forces acting on the lumbar vertebrae of the operator. Results from data analysis and simulations were analysed, compared, and evaluated against international and national standards from which judgments and conclusions could be made about the safety of machine operation in term of vibration. Collected data and results aligned reasonably well with what was predicted, however, due to some unavoidable variables during testing such as uneven gradient of ground and varying speed of the excavator, the resultant outcomes for vibration exposure and magnitudes were not accurate. This error opens the opportunity for further work to resolve these issues and produce results that present accurate conclusions.

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Limitations of Use

Certification

I certify that the ideas, designs and experimental work, results, analyses, and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Brad Chambers

Student Number: [redacted]

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Throughout the course of this project there where several people who greatly helped me achieve completion of all aspects of the project, I would like to share my gratitude and thanks by acknowledging these people.

Firstly, to my supervisor Dr Khalid Saleh who assisted and guided me through the project and supplied me with sources of helpful information.

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Finally, my friends and family, who encouraged and supported me throughout the year as well as allowing me to escape and destress from the workload at times.

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Table of Nomenclature

CAD	Computer Aided Design
FEA	Finite Element Analysis
WBV	Whole Body Vibration
VDV	Vibration Dose Value
ISO	International Organisation for Standardisation
AP	Antero-Posterior
USQ	University of Southern Queensland

CHAPTER 1

Introduction

1.1 Outline of the study

This report aims to investigate and study the effects that extended periods of cyclic vibration has on the human body while operating an excavator. The vibration frequency and intensity are to simulate those experienced by an operator of an excavator during general everyday operation of the equipment. Vibrational data will be collected from the excavator and then simulated using CAD software to determine the forces acting on the lower vertebra of the operator. The need for research into this topic initiated from experiencing firsthand experiences with earthmoving machine operators struggling with back and joint issues, the problem was a common factor with most of the operators.

1.2 Research Aims and Objectives

The intent of this research was to determine the effects that whole body vibration has on the human body as a result of the operation on an excavator. To achieve this, topics that relate to vibration, whole body vibration, and the human body will be investigated. It will focus on vibration and how it is transferred to the human body and the effects this has on components of the human body. The objectives for the study are:

- Background information relating to vibration, whole body vibration, exposure to vibration, the human body and its components, and material properties.
- What literature has been previously prepared that relates to whole body vibration, exposure to vibration, vibration sensors, and factors that affect how the body reacts to vibration.
- A small-scale vibration experiment that provides visual or analysable data on how vibration effects a material.
- FEA analysis that provides visual and numerical values for stress areas in a model representing a human body component.

1.3 Background and Idea Generation

The idea of the proposed research topic stemmed from a personal passion for, and experience in the earthmoving industry. Being a part of a family who owns a civil construction business, naturally I was introduced to heavy machinery from a young age and developed friendships with many machine operators over time. Knowing several machine operators and having worked and spent time with them, it became apparent that back issues were a common factor between them. Several of the older machine operators had required one or multiple surgeries in an effort to correct and resolve the damage that had been done which ultimately resulted in a significant time off work and limitations to bodily movements for an extended period of time, if not permanently.

Brief initial research into this topic proved that information regarding vibration exposure for excavator operators was scarce. Thus, there was a gap in the knowledge and a need for further research. This further research aims to focus on the specific type of heavy earthmoving machinery being the excavator and will investigate and evaluate the forces and effects that occur due to normal operation of the machine.

1.4 The Problem

The health and safety of an employee is always a high priority within any work force; thus, it is important we understand all risks involved in a person's role. This project idea plans to investigate the forces acting on a person's body while operating an excavator. A study by Zimmerman et al. (1997) investigated work related musculoskeletal symptoms in a group of 410 machine operators. Results from the study determined that lower back, neck, shoulder, and knees, in order from most common to least common, were the most prevalent musculoskeletal symptoms the sample of operators had reported. These statistics are evidence that the operation of machinery has an effect on the human body. This project will study the forces experienced by the operator and investigate potential methods or components that could reduce these forces acting on the body and ultimately provide a safer operating environment.

1.5 Dissertation Outline

This dissertation was designed to be structured in an orderly format that allowed for an easy-to-read report that flowed from section to section. The major headings for each chapter are listed below:

Chapter 1: Introduction – Offers a broad insight into what the dissertation entails. The introduction provides the basis of the report, identifies the problem, the gap in knowledge, and the need for this research.

Chapter 2: Background Information – The specific size of excavator to base the study off is selected and explained. Fundamental and background information is presented on relevant topics to the study such as vibrations, whole body vibration, and measuring vibration exposure, to supply the reader with some important knowledge relating to the rest of the dissertation.

Chapter 3: Literature Review – Information from previously composed reports and studies are presented, reviewed, and evaluated in the areas of vibration exposure of machine operators, effects of vibration on machine operators, vibrations sensors and their applications, and factors effecting how vibration effects the human body.

Chapter 4: Research Methodology – The processes and methods used throughout the entirety of the project to complete the various tasks required are detailed, explained, and justified. The majority of this section relates to how the data was collected and analysed.

Chapter 5: Results and Analysis – Results from the methodologies are presented in graphs created in excel and pictures of the FEA models from CREO. These results are analysed and discussed in detail.

Chapter 6: Discussion – A detailed discussion of the outcomes of the project aims, what was found, what went wrong, and what could be improved. An explanation of how the results could be used in industry is included.

Chapter 7: Conclusion – The final chapter of this dissertation to summarise the work that was done and results that were determined.

CHAPTER 2

Background Information

Chapter two will provide important and relevant information on the area of study to establish fundamental principles and knowledge to understand the purpose and importance of the investigation at hand.

2.1 What is Vibration?

In terms of mechanical engineering vibrations are periodic oscillations of a body or mechanical dynamic system displaced from its equilibrium position. There are two types of vibration, free vibration or forced vibration. Free vibration occurs when the motion is maintained by gravitational or elastic restoring forces, while forced vibration is caused by an external periodic or intermittent force [Dr. C. D. Tran, 2021]. Frequency, amplitude, spring constant, and damping factor are the most important engineering terms regarding vibration. Frequency, denoted by 'f', is a measure of complete vibration cycles per second, it is measured in hertz (Hz). Inversely proportional to the frequency of a vibrational wave is a variable called the period denoted by 'T', the period is the time taken to complete one full vibrational cycle [Airloc.com, 2022]. Mathematically frequency can be expressed as shown in equation 1.1, and the period of vibration for simple harmonic motion in equation 1.2.

$$f = \frac{1}{T}\ (Hz) \qquad 1.1$$

$$T = 2\pi\sqrt{\frac{m}{k}} \qquad 1.2$$

Amplitude is the variable that describes the power or severity of the vibration and is typically a measurement of acceleration or displacement. The value of amplitude is most commonly determined from a given vibrational sine wave on grid lines by measuring from its equilibrium to its peak, as portrayed by the illustration in figure 2.1.

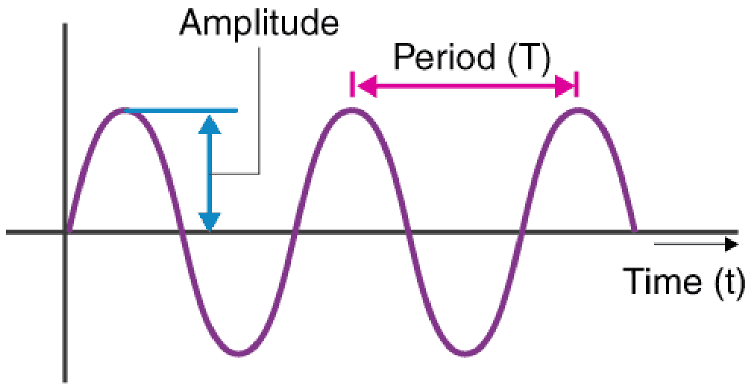


Figure 2.1: Measurement of amplitude and period of a vibrational wave. [Byjus.com, 2020]

Vibrations are present in every engineered system to some extent, in many cases the vibration is so minimal that it can be deemed negligible however, there are also many scenarios where vibration is very obviously present. When significant vibrations are occurring in a system it is important to understand whether they are deliberate and required for the function or application of the system, or if the vibrations will be detrimental to the function of the system. This analysis is done in the designing/analysis phase of a product, system, or operation by using computer aided design (CAD) software such as ANSYS to conduct simulations and analysis on components. These analyses include finite element analysis (FEA), and modal analysis which are capable of returning highly accurate and detailed results that even highlight areas of the component that will experience the greatest stress or strain thus allowing the engineer to accommodate for these forces [USQ, 2021]. Figure 2.2 shows a FEA model of a buckle from which the areas of higher stress are coloured red and colour to value scale on the left.

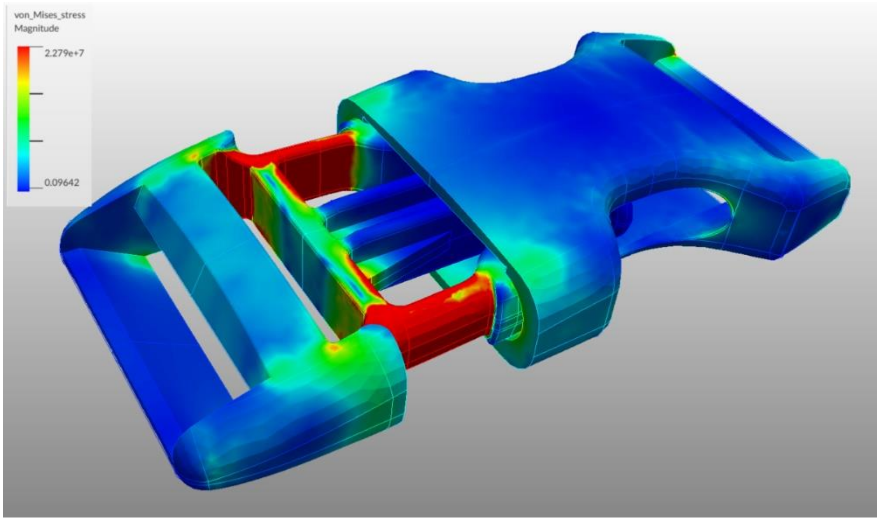


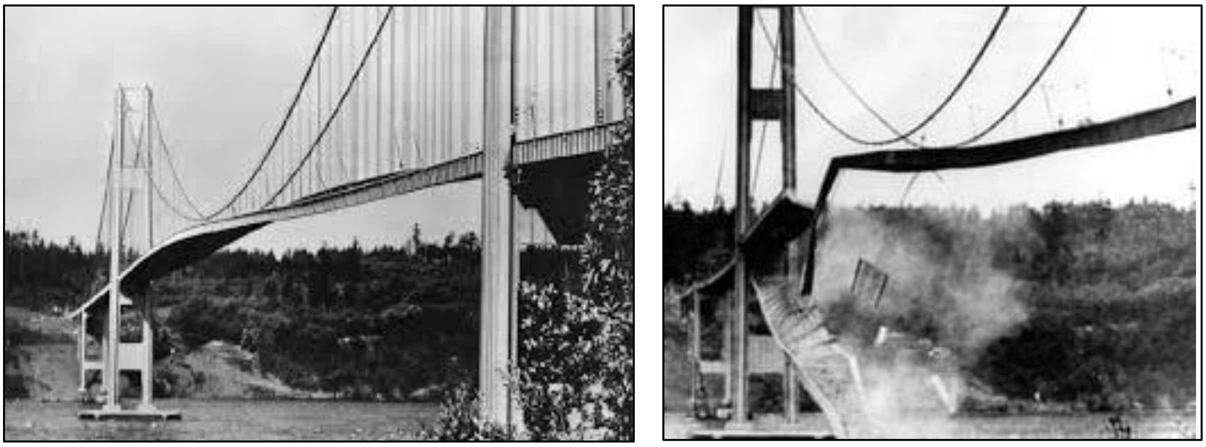
Figure 2.2: FEA model of a buckle highlighting areas of stress in red. [A. B. Harish, 2016]

2.2 Bad and Good Vibrations

Vibrations are a highly important variable and consideration for many applications in many industries and applications around the globe such as mining, automotive, and construction. These listed industries all require various forms of vibration in order to be successful and thus it is highly important for the vibration used to have the most appropriate properties to ensure success is achieved to an optimal standard and to assure safety for the surrounding environment. In simple terms vibration can either be good or bad for a mechanical system, vibration is considered good when the function of the system requires or is improved by vibration. Bad vibration is when the system experiences negative effects due to vibration such as causing poor performance. Vibrations can cause a wide range of issues within an engineered system that can affect the performance or safety of the system. These issues range from minor, where the consequences due to the vibrations are negligible, to catastrophic, in which vibration has caused serious injury or damage.

2.2.1 Bad Vibrations

It is no new fact that vibrations can be destructive, uncomfortable, and cause detrimental consequences in many cases. The definition of vibration states that it is when a system is displaced from its equilibrium position, thus it is predictable that when exposed to excessive amounts fatigue, wear, and failure could occur. Often in a vibrating environment a human is present as the operator of the system, passenger, or required to be in close proximity for other reasons, in these cases it is important that the vibration is at a level safe for humans. When designing high performance aircrafts this is a major consideration because when the resonant frequency of the human body is matched and exposed for sustained periods of time serious internal trauma can occur [J. Leatherwood & K. Dempsey, NASA, 1976]. An excellent example of when vibrations can become destructive is the Tacoma Narrows Bridge disaster in 1940. Due to this bridge having a new design compared to most other bridges at the time, an unforeseen source of vibration ultimately caused the destruction of the bridge. In windy conditions the bridge would experience violent torsional vibrations, as depicted in figure 2.3, which eventually caused failure of the structure. This same vibrational motion is also observed in aircraft wings which again can become catastrophic if the amplitude of the vibrations is too great as this would cause fatigue failure of the material [D. E. Adams, 2010].



Ffigure 2.3: Pictures from the Tacoma Narrows Bridge disaster showing the twisting of the bridge and the collapse. [J. Bashford, 1940]

2.2.2 Good Vibrations

In reading and when studying vibration, it is easy to adopt the idea that all vibrations are detrimental because there is such are large portion of content detailing the reduction of vibrations in systems. However, vibration can be beneficial for many applications and situations. As stated above mining, automotive, and construction industries use vibration for many purposes day to day. Vibration is used in mining to collect, separate, and sort materials effectively and efficiently. Similarly, in construction vibration is beneficial for the use of power tools such as jack hammers, or jigsaws which again improve the efficiency and effectiveness of tasks. In automotive the most common and important form of vibration system is the suspension, which allows for comfort and improved handling when driving a vehicle. The ability to detect vibration at very small magnitudes is also a benefit to vibration as it allows preventive measures to be enforced before any destructiveness occurs, this action is employed in many vehicles to increase safety. Good vibrations are common in all aspects of life and ultimately improve quality of life in many cases.

2.3 Machine Selection

Excavators are arguably the most common earthmoving machine in the civil construction, mining, and agricultural industries. They come in a vast range of sizes and shapes to best suit their intended purpose, ranging from one tonne up to 1000 tonnes. A mini excavator is the common term for any excavator up to six tonnes, this size of digger is typically used for small jobs that often require the operator to be in and out of the machine regularly. Excavators in the range of 13 tonne to 30 tonne are regularly used in civil construction companies as an effective primary tool to dig trenches for pipelines, pits, and many other applications where large amounts of material is required to be removed. This size range of machine requires a full-time operator, meaning an operator is working in the excavator for a full working day. Excavators above 30 tonnes are usually used for larger projects where very large quantities of material needs to be moved, such as highway construction or mines, these also require a full-time operator.

When deciding what size excavator to use as the subject for the investigation the main factor that was considered was the duration of time an operator is occupying the machine. This eliminated any mini excavator simply because when operating a mini excavator, the operator does not spend an entire working day in the machine. A mini excavator also does not produce vibrations as intense as the larger machines due to the smaller size.

Larger excavators such as the ones commonly found working in the mines or quarries produce significant vibrations from the enormous engines, from the action of breaking rock, and moving material. However, one of the most substantial forms of vibration when operating an excavator occurs when the excavator tracks to a different location. This action is rarely required from a large excavator working in the mines or quarries, it is more common for the material to be brought to the machine as this is a more efficient method of working.

The middle range of excavators (13 tonne to 30 tonne) were determined to have the most appropriate mix of variables and vibrations factors compared to the smaller and larger excavators. This size range requires a full-time operator, experience sufficient vibrations from typical tasks, and regularly track from location to location on site, access to a machine this size was also much more achievable. The exact size of excavator to be studied was a 21 tonne Komatsu excavator as this was easily accessible and all aspects satisfied the selection criteria. A picture of the chosen excavator is presented below in figure 2.4.

Figure 2.4: picture of the 21-tonne excavator chosen as the subject for the study. [komatsu.com.au]

2.4 Whole Body Vibration

Whole Body Vibration (WBV) is when vibrations from a supporting structure are transferred into the human body. This effect is most common when travelling in a vehicle or operating machinery, where the vibrations experienced and created are transmitted through the seat and footrest into the human body [Neil J. Mansfield]. In relation to this report, an example of WBV can be portrayed using an excavator operator. The excavator produces vibrations primarily when it is tracking, these vibrations are exposed and transferred to the operator through the seat, floor, and the arm rests. Although WBV is most common in these instances it is not limited to this, WBV can occur in any situation that involves vibration from an external source, which can be related back to almost any field of work or work environment.

WBV can produce a vast variety of effects to the human body depending on the duration and severity of the exposure. Typically, when an individual is exposed to WBV they will not experience any short-term effects, this is simply because the vibrations that are present in many cases of WBV are too small to cause any immediate damage. However, if the vibrations are strong the individual may feel discomfort or pain in certain areas of their body, commonly in their joints. Short term effects of WBV can be resolved and treated quickly and easily, however, it is the long-term effects that WBV can have on the body that raise concern. The most common result on the health of an individual as a consequence of WBV is pain in the neck and back, this is discussed in more detail in chapter three of this document along with other examples of the effects caused by WBV on the human body.

2.4.1 Measuring Vibration Exposure

When measuring and calculating the exposure of an individual to WBV axes x, y, and z are considered however, the axes with the highest average root mean square acceleration is used to calculate the daily vibration exposure A(8). The x and y axes use a 1.4 weighting (k) that reflects their contribution to health effects. Figure 2.5 depicts the standard orientation of the x, y, and z axes in the sitting and standing position.

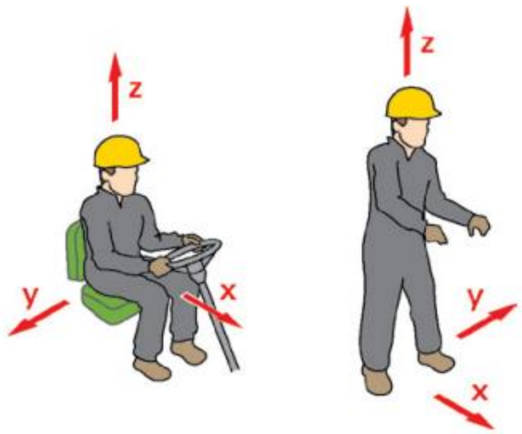


Figure 2.5: Standard orientation of axes of the human body in sitting and standing position [safeworkaustralia.gov.au, 2016].

There are two methods that may be used to measure exposure to WBV these are daily vibration exposure A(8) and the Vibration Dose Value (VDV). Daily vibration exposure A(8) is the quantity of WBV an individual is exposed to during an eight-hour working day, which take account for the magnitude and duration of vibration. The value for daily vibration exposure is derived from the magnitude of the vibration on the axis which has the highest weighted vibration magnitude and the greatest daily exposure duration [Safeworkaustralia.gov.au, 2016]. Mathematically the daily vibration exposure can be express as shown in equation 1.3. In the case that a person is exposed to more than one source of WBV then partial vibration exposures are calculated for each of the sources of vibration.

The total daily vibration exposure can be calculated using partial vibration exposure values by using equation 1.4.

$$A(8) = a_w\sqrt{\frac{T}{T_0}} \qquad 1.3$$

$$A(8) = \sqrt{A_1(8)^2 + A_2(8)^2 + \cdots} \qquad 1.4$$

Where:

- a_w is the vibrational magnitude in m/s^2
- T is the real duration of exposure to vibration in hours
- T_0 is the reference duration of eight hours.

The other method of measuring exposure to WBV is the vibration dose value, VDV is sensitive to peaks in acceleration levels and thus makes it the preferred measurement for exposure to shocks, jolts, and intermittent vibration. Compared to the daily vibration exposure value A(8), VDV returns a more representative value. The value of VDV is cumulative, meaning it increases with the measurement of duration. The value is determined and assessed by using the total time an individual has been exposed to a source of vibration per day and the length of time of the measurement. It is common for the VDV of the machine to be not publicly available, in this case the VDV must be measured. If however, the VDVs are available then the daily VDV for each axis can be calculated by applying equation 1.5, the resultant value has the units $m/s^{1.75}$. [safeworkaustralia.gov.au. 2016]

$$VDV_{exp,x} = 1.4VDV_x\left(\frac{T_{exp}}{T_{meas}}\right)^{0.25} \qquad 1.5$$

Where:

- VDV_x is the measured VDV on the x axis
- T_{exp} is the daily duration of exposure to the source of WBV
- T_{meas} is the time over which the VDV_x was measured

CHAPTER 3

Literature Review

This chapter will present, discuss, and evaluate findings from previous works and studies on relevant information to the aims and objectives of this report. Upon reviewing the research literature, a gap in knowledge will be established and thus the need further study.

3.1 Vibration Exposure of Heavy Machinery Operators

Many investigative studies have been conducted to determine the exposure heavy machinery operators have to whole body vibration. These studies have been performed with the aim of gaining a greater understanding of the effects WBV has on the health of the human body and use the results to help prevent any negative effects that may occur.

In 2007, A. P. Vanerkar performed a study investigating the WBV exposure in heavy earth moving machinery operators of metalliferous mines. The study had the specific aim to determine the degree of WBV exposure in a mining environment because at this time It had been proven that WBV caused musculoskeletal symptoms when over exposed however, there was little knowledge on its effects in specific industries. For this reason, the study was undertaken in two different types of mines in India, two bauxite mines and three iron ore mines, with a total of 5,500 employees across the five mines. the study was performed over a three-year period where WBV exposure was studied and examined twice every year at each mine site. The VDV was studied for the operators of heavy machinery and compared against the international standard for human response to whole body vibration ISO 2631. [ISO 2631, 1997]

The operators being assessed for WBV were in control of heavy equipment such as haul trucks, bulldozers, loaders, and excavators. The WBV of the operators was measured using an instrumented rubber disc which is placed on the operator seat so that the operator sits directly on it, a diagram shows this apparatus in figure 3.1.

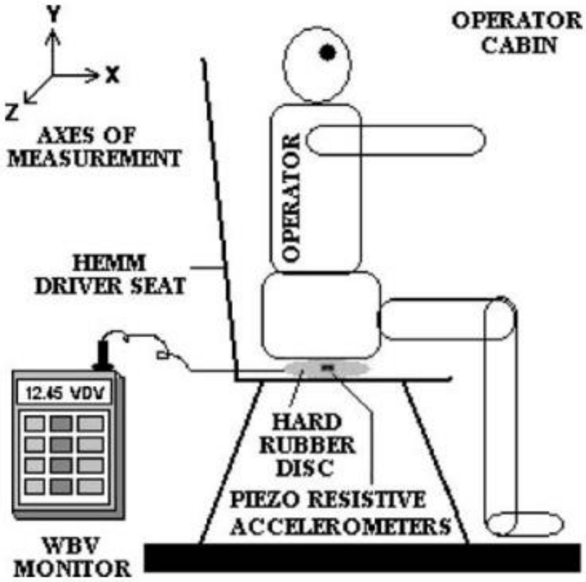


Figure 3.1: Measuring WBV of a heavy machine operator. [A. P. Vanerkar, 2007]

The measurement of actual time exposed to WBV depends on the duration of the work cycle, because of this, vibration levels were measured for as many work cycles as possible. This allowed for results to capture and reflect the differing vibration levels the mine workers experience over their working hours. The mining machinery was assessed to determine their VDVs, these were then evaluated using the international standards and guides for WBV.

Upon studying the VDV in the bauxite and iron ore mines, Vanerkar created a table for each to present the values in an orderly form, these are shown in tables 1 and 2. The tables included three sets of data for each machine type, these were the mean±SD, the range, and the percentage of higher VDV. The data presented was compiled from 141 readings for the bauxite mines (table 1) and 282 readings for the iron ore mines (table 2).

Table 3.1: Vibration dose values in bauxite mines

Sr. no.	HEMM type	Mine A	Mine B
		(Mean±SD)^n in m/s$^{7/4}$, range in (m/s$^{7/4}$), and % higher VDV	(Mean±SD)^n in m/s$^{7/4}$, range in (m/s$^{7/4}$), and % higher VDV
1	Dumper (n=60)	$(8.54\pm4.14)^{32}$, 4.54–18.12, 15.62%	$(10.12\pm3.67)^{28}$, 6.42–18.24, 17.86%
2	Dozer (n=20)	$(7.77\pm5.07)^{15}$, 4.62–18.20, 20.00%	$(13.97\pm2.54)^{5}$, 11.3–17.86, 20.00%
3	Drill[a] (n=20)	$(15.03\pm2.67)^{10}$, 12.7–19.21, 30.00%	$(12.03\pm3.87)^{10}$, 8.00–18.36, 20.00%
4	Loader (n=26)	$(8.93\pm6.0)^{13}$, 4.57–19.16, 23.08%	$(10.81\pm5.29)^{13}$, 4.77–17.89, 30.77%
5	Poclain (n=15)	Not available	$(5.33\pm4.76)^{15}$, 2.07–16.88, 13.33%

Table 3.2: Vibration dose values in iron ore mines

Sr. no.	HEMM type	Mine C	Mine D	Mine E
		(Mean±SD)^n in m/s$^{7/4}$, range in m/s$^{7/4}$, and % higher VDV	(Mean±SD)^n in m/s$^{7/4}$, range in m/s$^{7/4}$, and % higher VDV	(Mean±SD)^n in m/s$^{7/4}$, range in m/s$^{7/4}$, and % higher VDV
1	Dumper (n=120)	(10.93±2.95)^{66}, 7.71–18.00, 16.67%	(5.38±3.54)^{13}, 3.50–17.10, 7.69%	(12.33±2.58)^{41}, 9.11–18.00, 19.51%
2	Dozer (n=48)	(10.18±3.09)^{10}, 8.50–18.30, 10.00%	(11.43±3.52)^{19}, 8.27–18.30, 21.05%	(10.48±4.33)^{19}, 7.02–18.60, 26.31%
3	Shovel (n=72)	(5.63±5.65)^{36}, 0.932–18.10, 16.66%	(5.52±5.32)^{14}, 1.82–18.00, 14.28%	(5.21±5.39)^{22}, 2.36–18.00, 18.18%
4	Drill[a] (n=42)	(4.88±4.35)^{10}, 2.42–16.8, 10.00%	(4.27±4.39)^{10}, 2.07–16.6, 10.00%	(3.35±4.26)^{22}, 1.07–17.10, 9.10%

Using these tables of results the VDV and the higher percentage of recorded values for VDV was calculated for each machine type and a new table was created to allow a cross comparison between the operators of the two types of mines, this is table 3. The purpose if this comparison was to determine whether the operators of the same machines, undertaking very similar work patterns and processes experienced any significant difference in WBV exposure. Reviewing the comparison between results, it became obvious that there was no significant difference between the results obtained from either mine. The values for the iron ore mine were slightly greater than from the bauxite mine however, these results were not strong enough to claim one to cause more WBV than the other, and thus it was deemed that the results indicated that WBV exposure is not dependent on the type of mine.

Table 3.3: VDV for heavy machinery operators

Sr. no.	HEMM type	Bauxite mines		Iron ore mines	
		VDV (mean±SD)^n in m/s$^{7/4}$	Percent higher VDV	VDV (mean±SD)^n in m/s$^{7/4}$	Percent higher VDV
1	Dumper	(9.27±3.98)^{60}	16.74	(10.81±3.44)^{120}	14.62
2	Dozer	(9.32±5.28)^{20}	20.00	(10.79±3.75)^{48}	19.12
3	Loader/Shovel	(9.87±5.63)^{26}	25.00	(5.48±5.43)^{72}	16.37
4	Drill	(13.53±3.58)^{20}	26.92	(3.93±4.25)^{42}	9.70
5	Poclain	(5.33±4.76)^{15}	13.33	Not available	Not available
6	Student's t test value, 1.12 (non-significant)				

The most prominent difference in values came when comparing the values associated with each machine in the sample space. It was observed machines that travelled around the site such as haul trucks and loaders returned higher values of VDV than those that spend more time in a stationary position, such as a shovel or excavator. This was expected to occur due to the added jolts and shocks that naturally occur when traveling around a mine site due to uneven surfaces and forces that come with dumping, loading, and being loaded. The mines sites being examined had limited excavators, thus producing less data to evaluate for this type of machine, therefore, further emphasising the gap in knowledge and the need of further study.

Table 3.4: VDV bauxite mine compared to iron ore mine

Sr. no.	Type of mine	Mine	VDV (mean±SD)^n in $m/s^{7/4}$	Percent higher VDV	VDV (Mean±SD)^n in $m/s^{7/4}$, % Higher VDV
1	Bauxite (n=141)	A	$(9.37\pm5.07)^{70}$	22.17	$(9.57\pm4.93)^{141}$, 21.28%
		B	$(9.77\pm4.83)^{71}$	20.39	
2	Iron (n=282)	C	$(8.80\pm4.81)^{122}$	13.33	$(8.21\pm5.12)^{282}$, 14.95%
		D	$(7.27\pm5.06)^{56}$	13.26	
		E	$(8.58\pm5.47)^{104}$	18.27	

3.1 Effects on the operator

In reviewing literature related to the proposed topic, articles were found that studied exposure to whole body vibration among heavy equipment vehicle operators. The role of heavy equipment machinery operators is to maintain and operate heavy machinery and equipment used in the construction and earthmoving industries. Compared to other workers in the construction industry such as laborers and tradesmen, operators experience a substantially separate set of stressor factors on the body. The stressors that machine operators are exposed to during operation include, sustained awkward postures, noise, and whole-body vibration. These risk factors slowly and subtly weaken the human body, particularly at the joints. [Chris L. Zimmerman, 1997]

Chris L. Zimmerman conducted a study where 410 machine operators participated in a survey questioning about musculoskeletal symptoms. The study was conducted on operators over a large range of ages from 22 to 71 and a large range of time working as an operator, from one year to 50 years, this age distribution is displayed by the pie charts in figure 3.2.

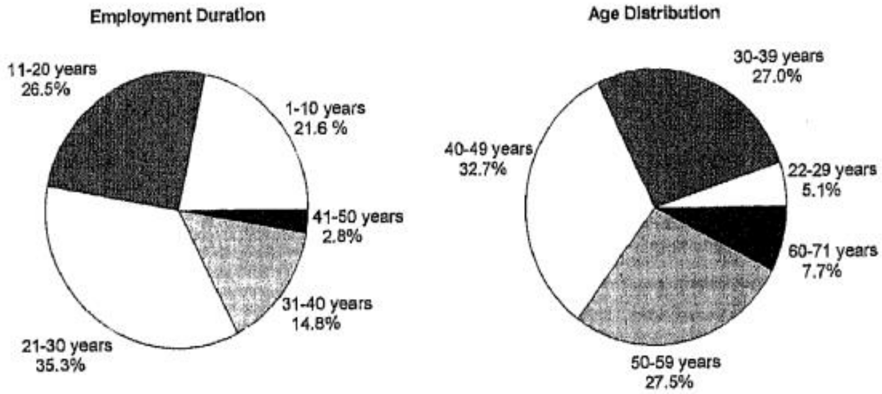
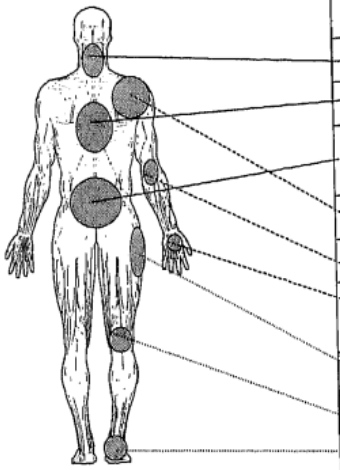


Figure 3.2: Distribution of machine operators by employment duration and age. [Chris L. Zimmerman, 1997]

The survey collected information such as self-reported work-related musculoskeletal symptoms, missed work, physician visits, the area of the body that was an issue and a summary of operating time over the last 12 months. The results showed that work related musculoskeletal symptoms were most prominent in the lower back 59.9% of the sample reported, neck 43.8%, shoulders 36.8% and knees 32.0%, these statistics are displayed in a table and accompanying human body diagram in figure 3.3. Workers who had a longer working history consistently reported higher percentages of symptoms, physician visits and time off work compared to the group of less experienced workers. This suggests that operating time is a major contributor to musculoskeletal symptoms in operators (Chris L. Zimmerman, 1997).



Anatomic Region	% Job Related Pain	% Missed Work	% Physician Visits
Neck	43.8	1.6	19.7
Upper Back	24.1	1.4	13.3
Lower Back	59.9	7.8	25.0
Shoulder	36.8	2.2	12.4
Elbow	18.2	0.6	3.4
Hand / Wrist	29.7	2.5	5.9
Hip / Thigh	16.4	1.4	6.4
Knee	32.0	1.1	4.6
Ankle / Feet	18.6	2.8	6.6

Figure 3.3: self-reported musculoskeletal symptoms, missed work, and physician visits among a sample of machine operators. [Chris. L. Zimmermann, 1997]

The areas of the body that experienced symptoms greatly differed between the various machines the operators were in control of, these included bulldozer, backhoe, crane, scraper, and front-end loader. Operators from the same machine type consistently reported similar symptoms in the same areas of the body, this suggest that machine specific stresses must be present. Note that an excavator was not a machine included among the range of heavy equipment vehicles, opening an area of work that requires further study due to a gap in knowledge. Another factor that formed a pattern in reported symptoms was the age of the machine in operation, a higher percentage of operators reported missing work and physician visits due to musculoskeletal symptoms were from a group who operated older machines. This is due to less advance suspension and seating systems within the cab of the machine. (N.K. Kittusamy 2004)

A similar study was conducted in 1987 by H. Dupuis, and G. Zerlett where a group of 352 heavy equipment operators with a minimum of three years' experience were studied. This investigation gathered the medical histories and X-rays of 251 of the participants spines. This sample of people were compared against a control group of 315 participants who worked in similar environments however were not exposed to vibration, 151 X-rays of the spine were available from the control group. The two groups were asked to describe and rate their pain or discomfort in their back after an eight-hour working day. The results from this analysis revealed that the operators reported considerably more pain and discomfort throughout the day compared to the control group. During a working day, the percentages from each group that had report discomfort were: operators 75%, control 49%, after work: 59%, 45%. Reviewing the X-rays discovered that the operators had more spinal disorders than the control group (70% vs 54%), these included issues such as deteriorating discs, enflamed joints, and lumbar syndrome. The lumbar region (lower back) was determined to be the area that caused the operators the most discomfort compared to the control group (69% vs 42%). Another trend among the groups was the older participants experienced a significantly greater amount of discomfort, pain and health issues compared to younger workers, this result was expected. The study concluded that whole body vibration causes morphological changes in the spine, particularly the lumbar region when exposed to it long term.

3.2 Vibration sensors

A vibration sensor is a device used to measure the intensity and frequency of vibration present in a system. They are commonly on any system, piece of equipment or machine to monitor the vibrations to detect for imbalances or any issue that may cause damage to the system.

There are seven different forms of vibration sensors, each having a particular application within an industry. These types of sensors include:

3.2.1 Strain Gauges

A strain gauge is a foil or thin wire that attaches directly to the surface of the system being analysed. As the material that the gauge is attached to stretches and compresses the electrical resistance of the foil or wire is altered and thus a measurement can be taken by timing how long it takes for an electrical current to pass through the gauge. Vibration is measured using a strain gauge by observing the straining of the material. Strain gauges are useful for curved or uneven surfaces as they can conform to the shape of the object. This type of gauge is inexpensive however, equipment required to read the data from the gauge can be costly. [Katalin Agoston, 2016]

3.2.2 Accelerometers

An accelerometer is a sensor that measures forces due to acceleration acting on an object. Electrical signals are produced in the accelerometer each time acceleration changes, this electrical signal is interpreted to provide vibrational data. There are three different types of accelerometers, these are: piezoelectric, piezoresistance, and capacitive, each type is designed to optimise function in different environments and applications. Accelerometers offer two options for axial data, single axis and triaxial. Single axis accelerometers are more common and used to measure mechanical vibration levels, whereas triaxial accelerometers are used to determine the type of vibration i.e., transverse, lateral, or rotational. It achieves this by creating a 3D vector of the acceleration present in the form of orthogonal components. [ni.com, 2020]

The piezoelectric accelerometer utilises the piezoelectric effect to detect change in acceleration. The piezoelectric effect is observed when electricity if produced due to physical stress of a material. This type of accelerometer is often used to measure vibration and shock.

A less sensitive accelerometer compared to the piezoelectric is the piezoresistance accelerometer, with this type of accelerometer resistance and pressure are proportional to each other such that resistance increases in the accelerometer with more pressure applied to it. The piezoresistance accelerometer is useful for taking higher shock range measurements such as vehicle safety testing or weapons testing.

The final type of commonly used accelerometer is the capacitive accelerometer, this type has a similar operation to the resistive accelerometer however measures a change in capacitance instead of resistance. Capacitive accelerometers are widely used in computers, smartphones, vehicles, and other small electronic devices to detect movement, such as in a smart phone when it is tilted.

3.2.3 Inductive Sensor

An inductive sensor, also known as an eddy current sensor, is a non-contact sensor used to measure position, displacement, oscillations, and vibrations. They offer highly precise and accurate measurements and are useful in harsh environments since they are not affected by pressure, temperature, dirt, or oil [Dr. Subrata Jana]. Inductive sensors are used in industry for applications such as measuring vibration in steel galvanising plants, measuring cylinder position in internal combustion engines, measure movement in hydraulic cylinders, and aeroplane landing gear.

3.2.4 Laser Displacement Sensor

A laser displacement sensor is another form of contactless sensor, this type of sensor uses triangulation with a transmitting and receiving lens. A laser beam is shot through a transmitting lens onto the object being observed, this beam reflects off the target into a light receiving lens which directs the laser into the light receiving element. As the target moves the angle at which the laser reflects at changes thus hitting the receiving element at different positions allowing precise measurements to be taken. Laser displacement sensors are used in applications where other sensors may not operate desirably such as rotating components, or in applications where the mass on a sensor would disrupt the motion of the system [Steve Hanly, 2021].

3.2.5 Acoustic Pressure Sensors

Vibrating objects create sound waves, these sound waves can be captured and observed allowing vibration to be detected. Acoustic pressure sensors, more commonly known as microphones can detect and provide basic vibrational information such as changes in vibrational frequency. A microphone has a basic structure of a pressure sensors, it consists of a diaphragm and a displacement transducer that converts the deflections from the diaphragm into electrical signals. There are many variations of microphones that differ by their directional characteristics, frequency, sensitivity, dynamic range, bandwidth, and sizes [Jacob Fraden, 2016]. Acoustic pressure sensors are useful for detecting weather vibrations are present in a system and the frequency of these vibrations however since they do not provide many details or more vibrational data the applications for specific measurements of vibration are limited. [Fraden, J., 2016. Handbook of modern sensors physics, designs, and applications].

The above descriptions of various different types of sensors that are capable of detecting vibration outlined that the most appropriate and useful sensor to use for the intended purpose of measuring vibration present during operation of an excavator would be an accelerometer. This will allow for measurements to be taken in the desired axial orientation that will best illustrate and portray the vibrations experienced by the machine operator.

3.2.6 Mounting an Accelerometer

The mounting of an accelerometer or any vibration sensor is highly important because it has a direct impact and influence on how well the device performs and collects data. It is vital to mount the sensor correctly and securely to ensure true readings and measurements. If the sensor is mounted incorrectly, the instability of the sensor may add data that does not reflect the actual vibration of the target and thus the data would be deemed inaccurate and unreliable. [Hansford Sensors, 2015]

The method of mounting that provides the best results is stud mounting, this is when a hole is drilled and tapped into the structure being measured and the accelerometer is screwed into the hole essentially making the accelerometer one with the structure, for best results a form of lubricant such as grease, or petroleum jelly should be used in conjunction, this fills any imperfections in the surface of the structure thus creating better surface contact. [Steve Hanly, 2017]

3.4 Human Body

3.4.1 Posture

In order to understand how the machine operator's body is affected during operation of the excavator, it is first important to confidently know the specific areas and joints on the human body that would be most exposed and susceptible to vibration because then specific area of the body can be observed, modelled, and simulated to determine exactly what effects vibration has on a particular part of the human body. The most prominent factor determining this is the posture of the operator during operation.

Posture is defined as the position in which an individual holds their shoulders, neck, and back, or a particular position when standing or sitting [Cambridge Dictionary, 2022]. The action of operating an excavator is performed in the sitting position with both arms half extended forwards holding the joy sticks. A major factor in determining the stressors on the body while in a seated position is the posture of the individual [C. Bontrup, 2019]. The angle at which the individual's body is in reference to the vertical axis will affect which areas of the body are experiencing more or less stress. These stressors are due to the downwards force of gravity and the mass of the human body against the upwards force of the seat. The illustration in figure 3.4 provides a simple example of three common sitting postures showing the angle of the spine relative to a standard x-y axis and indicating the good posture position and the bad.

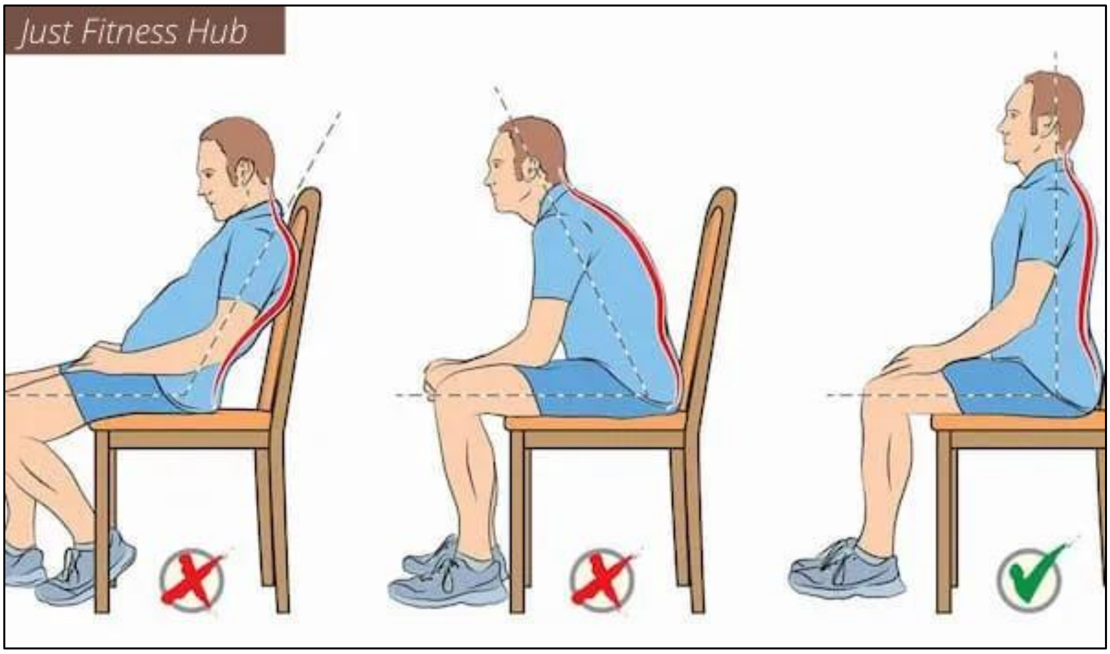


Figure 3.4: Common posture positions while seated

The three postural positions above are known in general terms as slouch, slump and straight, each position corresponds to an angle where the spine and upper legs meet. The ideal seated angle is said to be 90 degrees, which as seen in figure 3.4, is the straight position, this position allows for equal distribution of forces on the spine, pelvis, and legs, and thus reduces the chance of localised pain as well as future skeletal disorders such as kyphosis and lordosis which are common issues as a result of slouching and slumping [S. Kripa, 2021]. While sitting in a slouched position, extra stress is present in the neck, lower back, and the knees of the individual. The slumped position creates extra stress in the lower back and pelvis region.

A study by Y. Kwon in 2018 investigated the antero-posterior (AP) reaction force at the cervico-thoracic (neck) and lumbosacral (lower back) joints for various sitting postures. In addition to the sitting posture, two arm postures were also tested in conjunction with the sitting posture, these were arms on chest and arms forward. In this study twenty healthy males participated, the population had spinal curvatures of slump, flat or lordosis. Kinetic and kinematic data was collected from these sitting postures, using inverse dynamics the AP reaction forces and joint moment could also be calculated.

AP reaction forces and joint moments were calculating using an Interactive Musculoskeletal Modelling software by entering the measured forces and movements into the system. By adding the mass of the tested individual, the model could return accurate results for the forces and moments experienced in joints of the neck and lower back.

The results from this study proved that when in the slumped position, both the cervico-thoracic joint and the lumbosacral joint produced a greater AP reaction force compared to the other two positions, which relayed similar results to each other. Having the arms positioned forward or on the chest did not have a considerable effect on the slumped posture however, the AP force in the neck when the posture was flat, or lordosis was 20% greater than when the arms where on the chest. The difference for the lower back was negligible. The results for the AP forces for the neck and the lower back joints are displayed in figure 3.5 and 3.6 below.

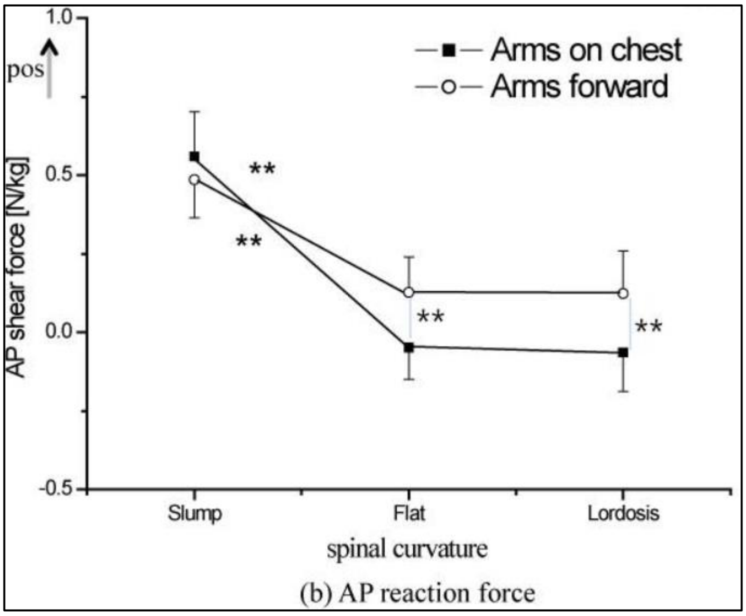


Figure 3.5: AP shear force on the cervico-thoracic joint (neck) [Y. Kwon, 2018]

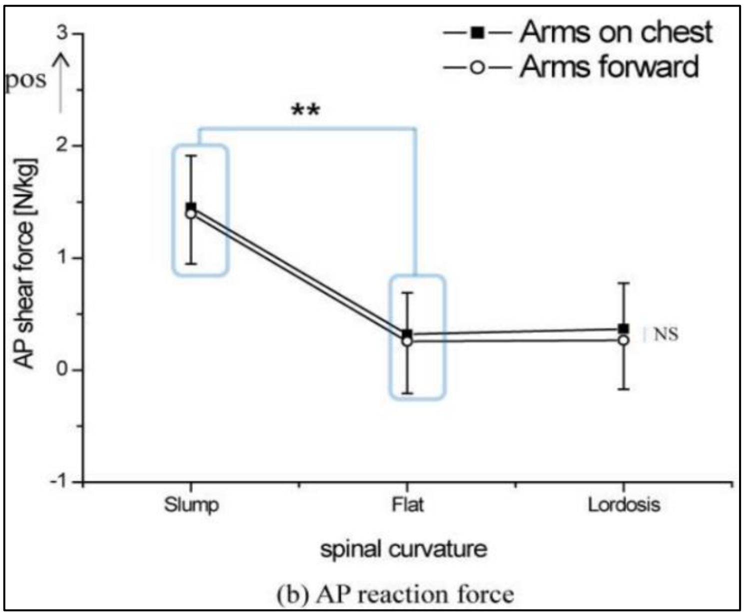


Figure 3.6: AP shear force on the lumbosacral joint (lower back) [Y. Kwon, 2018]

The research and results from this study are important and must be accounted for in this report because an excavator operator performs their work while seated, and thus the posture they assume during operation each day will have an effect on which parts of their body that will be most affected. Due to the position the excavator operator is in whilst operating and the actions they must perform in order to control the machine such as moving the joy sticks or pushing/pulling the levers to move the machine forward or backward, it is typical that the operator will lean forward or adopt a slumped posture as it can allow for ease of access to the controls, allow for greater visibility, or improve concentration while operating.

The results gathered by Y. Kwon determined that when an individual is in a slumped position, the joints in the lower back and neck region of the body experience the greatest shear force. From this information it can be expected that this area of the body would be most likely to develop pain or health related issues over time.

3.4.2 Human Vertebrae Properties

An understanding of the composition of human joints is vital for this investigation because it was determined that the joints were the most common areas where pain was experienced according to the above literature. Knowledge of the structure and components of joints in the human body is important as it will allow us to deconstruct, analyse, evaluate, and simulate the problematic area to determine what exactly is being affected within the joint to cause pain to an individual.

Anatomically, a joint is defined as a part of the body where two or more bones meet to allow movement [betterhealth.vic.gov.au, 2012]. Joints are complex structures made up of bone, muscle, synovium, cartilage, and ligaments that are designed to bear weight, move the body, and dampen forces [C. Benjamin, medlineplus.gov, 2021]. Upon reviewing the literature above, it became clear that lower back pain was the most commonly reported issue among heavy equipment operators. For this reason, spinal vertebrae in the lumbar region will be further researched and used as the focus joint for the analysis and experiments in the later chapter of the report.

Figure 3.7 illustrates the lumbar section of a human spine, within this image the vertebrae bone, intervertebral discs, spinal nerves, ligaments, facet joints, and spinal cord. The intervertebral discs lie between each vertebra in the vertebral column and consist of a fibrous cartilage outer layer and gelatinous core. Each disc forms a fibrocartilaginous joint which was multiple functions that are, allowing movement of the vertebrae, holding the vertebrae together, and to act a shock absorber for the spine. These discs are soft but not compressible and thus susceptible to herniate, which is commonly referred to as a ‘slipped disc’. Several studies have proven that the structural integrity of an intervertebral disc deteriorates with age making them much more susceptible to damage as age increases, which can ultimately cause sever pain for an individual.

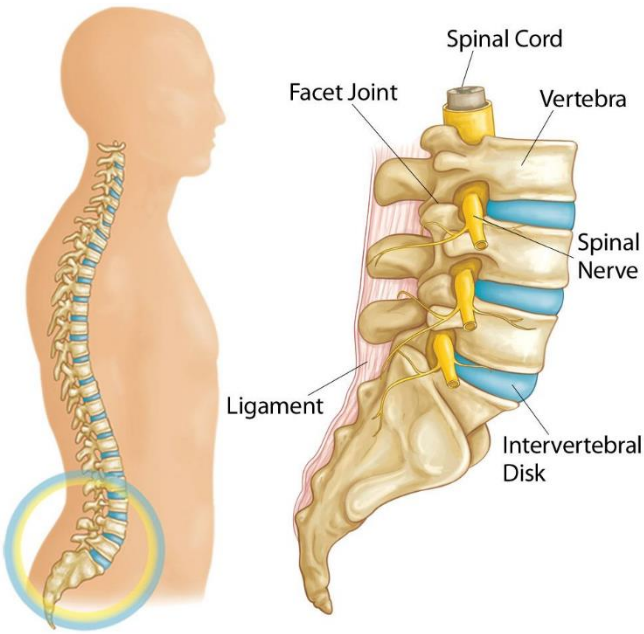


Figure 3.7: Diagram of lumbar region of human spine. [orthoinfo.aaos.org]

The vertebral body is made of thick oval segmented bone which has evolved to adopt certain properties and structure to achieve optimal performance for the compressive and tensile forces that are constantly acting on the component. A study by Ebbe N. Ebbesen on the compressive strength of the vertebral body in relation to age determined that the average compressive strength ranges from roughly 12kN to 2kN with an average of 6.5kN. The maximum compressive stress ranged from 9MPa to 1.5MPa with an average of 4.6MPa. The results from this study showed a drastic linear decline in strength and stress of the vertebrae as age increased.

Chapter 4

Experimental methodology

This chapter will address and explain the actions and methods that were performed to complete the project. This section will focus on the data collection and analysis phases of the project, however, will include methodology involved in the writing and preparation of the dissertation, safety, timeframes, and resources.

4.1 Overview

The data collection stage of this research project includes two modes of data collection and analysis, these are:

- Physical
    - Data collection using Arduino

- Computational:
    - Graphing vibrational data
    - FEA analysis

Physical Data Collection: Allows the results to be associated with the specific type of excavator operator in terms of industry, in this case, the excavator is working in the civil construction industry. Typical tasks an excavator and its operator will perform in this industry include digging trenches, digging drains, clearing land, lifting heavy objects such as pipes/precast concrete pits, and tracking to different locations on the job site. An accelerometer will be attached under the seat of the excavator and allowed to collect data from the X, Y, and Z axis for a period of time, this was more desirable than using vibrational data found in research as it allows for a greater understanding of the source of the vibration as well as a data set tailored to specific needs of the project. This data will then be transferred to Microsoft excel where the data can be sorted, graphed, and analysed.

Computational: Data computing and analysis programs such as excel and CREO will be used to provide quantifiable data to help ascertain the forces acting on the operator. Data from the accelerometer will be imported into Microsoft excel when tables and graphs will be created which will allow the vibrational wave to be visually observed and analysed.

Performing an FEA analysis on a human vertebra using the forces calculated from the data values collected from the excavator will provide a visual and quantitative understanding of the exact forces that are acting on the component and the areas of the vertebrae that are most susceptible to these forces.

4.1.1 Timeframe

This project is allocated a course in both semester 1 and 2 of the academic year. First semester begins late February, and the final dissertation document is due mid-October, giving the student approximately seven months to complete the research project. To help aid progress and time management throughout the year a Gantt chart was created with a which gave suggested timeframes to complete the different phases of the project. The Gantt chart is included in Appendix C at the end of this report.

Project Preparation: This phase includes all the initial setting up and learning required to complete the project, such as getting the project idea approved by the USQ staff and supervisors, initial communications with the supervisor to refine the project idea and process, collecting background information on relevant topics to gain fundamental and foundational knowledge, reviewing literature to better understand the topic and processes that have been used in previous works, and the methodology which details the process and techniques that were used and implemented to collect and analyse data.

Data Collection: All relevant information regarding the ability to collect data from the excavator and computationally is included in this phase. Planned to begin around the start of semester two, this stage includes tasks such as obtaining the required sensors and electronics from JayCar needed to successfully record axial data from the excavator. Coding the Arduino to appropriately talk to the sensors and devices connected to it in order to collect and record the required data with help from the mechatronic engineering team at USQ. Transferring the recorded data into excel to create graphs and tables that show the vibrational wave for each axial direction.

Modelling: The 3D solid modelling program CREO was used to create a model of a human vertebra by using a picture with dimensions as reference. The collected and calculated vibrational data was then able to be entering into CREO as forces and then simulated. This allows for a highly accurate calculation and visualisation of the effects on specific areas of the vertebra.

Analysis & evaluation of results: The results accumulated from the FEA were discussed in the discussion section of the report. The results were compared and evaluated against standards and limits found online. This enabled a judgment to be made on the effects experienced by the excavator operator and whether or not action had to be employed to reduce these effects.

Dissertation: The dissertation was worked on and updated continuously throughout the year with guidance from my supervisor, Khalid, who gave helpful advice when it was needed. The document as a whole was summarised and a short power point presentation was made to present the work at the on-campus seminar. The final weeks before the due date was allocated to finalising results and conclusion, making the document look professional, and fixing any errors that may be present.

4.1.2 Resources

The majority of this research project was theoretical and computational but also required an aspect of physical data collection. The total number of resources needed to complete this research project was purposely kept to a minimum, this was done to reduce the overall cost of the project, note that some of the required resources were already in possession prior to starting this project due to previous applications. This mindset also resulted in keeping the project simple and achievable by discouraging the addition of other experiments and variables that required testing and analysis. The resources required to complete all areas of the project are listed below.

Already acquired:

- Arduino uno
- MPU6050 Gyro/Accelerometer
- Battery pack
- Jumper wires

Need to purchase:

- SD card reader & SD card
- Duct tape
- Pack of AA batteries

Need access to:

- 21T Excavator (Bob Chambers PTY/LTD)
- CAD software (CREO Parametric)
- FEA software (CREO Simulate)
- Microsoft Office
- Arduino software
- Computer
- Internet access
- Transportation

4.2 Data Collection

The collection of vibrational data directly from the excavator was accomplished using an Arduino Uno microcontroller with an accelerometer and SD card reader wired and programmed together. This apparatus was secured to the frame of the seat within the cabin of the excavator using tape. It was important to position the accelerometer so that the X, Y, and Z axis lined up with the same orientation as illustrated on the sensor itself, as this would enable the sensor to return the most correct, accurate, and understandable data. Since the seat of the excavator uses a suspension system and has cushioning the data collected from the frame of the seat would not accurately portray the vibrations the operator is actually experiencing. The data that was collected was the vibrational forces that are transmitted into the springs and dampers of the seat and then into the operator. Therefore, to assess the resultant data correctly the springs and dampers within the seat must be accounted for, which was done later in the project. Once the device was adequately secured to the excavator, it was plugged into the battery pack and allowed to collect data for a period of time while the excavator performed some general operational tasks.

This method of data collection aimed to help provide an understanding of the vibration experienced by the operator of an excavator by gathering data values that could be used to create graphs of the vibration in each axial direction in the form of acceleration against time. The ideal results from the analysis of the data collected will indicate critical values such as peak values of vibration and average vibrational values from which a judgement could be made on the effects caused to the operator.

4.2.1 Arduino

As stated above, an Arduino Uno was used to collect and store vibrational data from the excavator. An Arduino Uno is a small, commercially available, easy to use microcontroller that has a huge range of functions and attachments allowing to be used for many different purposes. The sensor used with the Arduino for this project was the MPU6050, which consists of a three-axis accelerometer and a three-axis gyroscope. It is able to measure orientation, velocity, acceleration, displacement, and other motion features. For the purpose of this project the MPU6050 was programmed to return data values for acceleration in all axial directions and displacement in the vertical direction, these values were then graphed against time to create visual representations of the vibration. In order for the components of the Arduino to work the way they were intended, and to produce the desired outputs, a code had to be written to tell the Arduino to perform the required tasks. The entire code used can be found in Appendix E. Dr Tobias Low from the mechatronics section at USQ must be acknowledged as he helped write, troubleshoot, and refine the code to the point where the returned data was satisfactory. Below are pictures of the components that made up the data collection device.

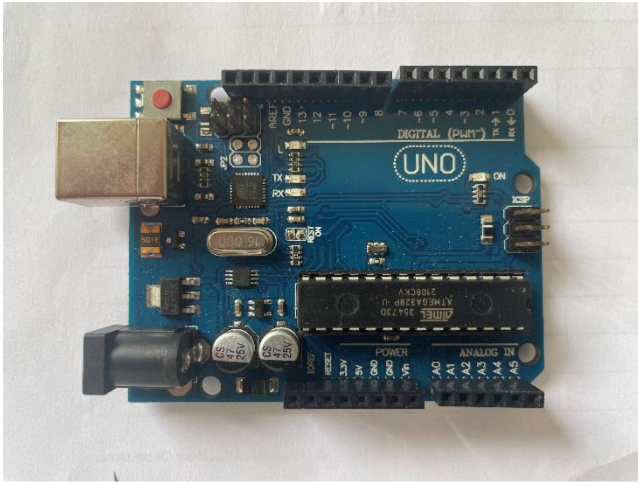


Figure 4.1: Arduino Uno microcontroller

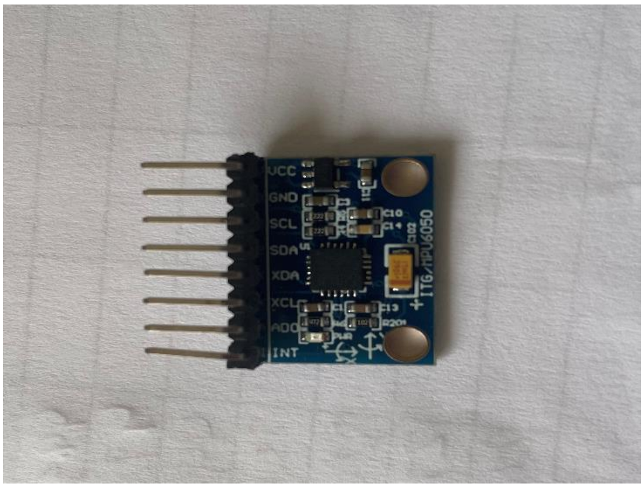


Figure 4.2: MPU6050 Gyroscope/Accelerometer

4.2.2 Setup

Having wired the accelerometer to the Arduino board correctly and securely it was time to attach the device to the seat of the excavator in a position that would allow it to collect appropriate data. To assure the data that was collected was able to be read and understood easily the accelerometer had to be oriented so that it was lined up with the axial directions as printed on the sensor itself. Setting up the accelerometer in such a way is crucial for the sensor to return data that is easy to understand and analyse. This is because when the accelerometer is lined up correctly with its axial directions the returned values for the horizontal axis will be zero and the vertical axis will be 9.81. The accelerometer was orientated so that the X axis was vertical (pointing to the sky), the Y axis was orientated to the left and right of the operator, and the Z axis was facing in front of and behind the operator. The Arduino apparatus was secured in place on the metal frame under the seat using duct tape, this set up is pictured below in figure 4.4. Duct tape was utilised because it was a simple yet effective method that kept the sensor tightly secured. The location on the seat where the sensor was attached was first investigated to make sure that the particular area moved with the suspension system of the seat, this measure was taken to assure the data collected aligned with what the operator experiences during operation of the machine.

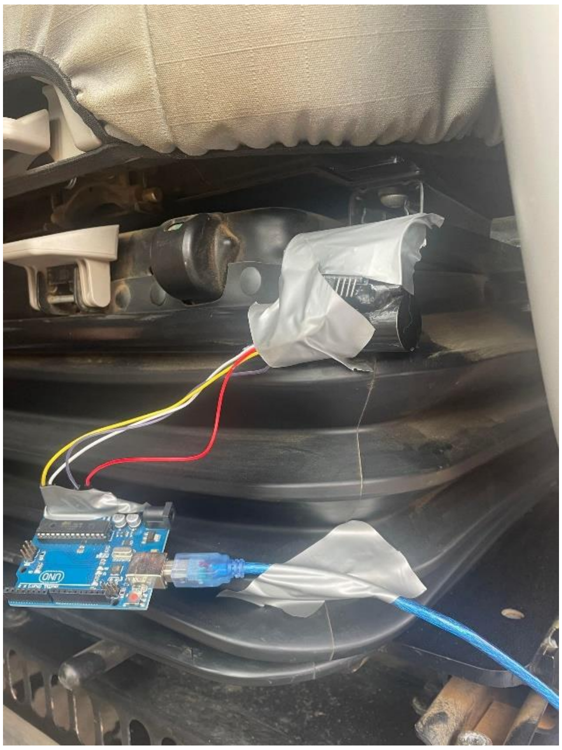


Figure 4.4: Picture of how the Arduino apparatus was attached to excavator seat

4.2.3 Procedure

Once the Arduino apparatus was mounted securely to the seat of the excavator, the device was supplied power by plugging it into a USB port on the laptop that sat under the seat. Now, on the Arduino IDE program on the laptop, the serial monitor was opened allowing the axial data the be collected and recorded. With the accelerometer now correctly gathering data, the operator of the excavator was instructed to perform several general tasks. The excavator tracked approximately ten meters from its starting position to pick up a bucket before pivoting and tracking a further 30 meters over to a pile of dirt. Once arrived at the pile of dirt the operator changed buckets and began to dig and spread out the pile of dirt. Pictures of the excavator during the period of data collection are shown below in figures 4.5 and 4.6.

Figure 4.5: Excavator tracking 40m to pile of dirt

Figure 4.6: Excavator digging and moving material

The tri-axial acceleration data was collected over a short period of five minutes which is a very short period of time relative to a full working day, however, the actions performed during this time provided adequate data to represent the vibrations that occur during general operation of the excavator. The entire list of data values was copied and pasted into excel where they could be analysed. The testing was carried out on a relatively smooth surface and with slight deviation in elevation changes. This surface was considered to be more level and smoother compared to other common terrain types that an excavator typically operates on.

4.3 Computational Methodology

The Computational side of this investigation was undertaken to analyse the data collected via graphs and simulation software. By importing the data values collected from the excavator into various computer programs such as excel and CREO Simulate, it was possible to create graphs and simulation models to visually observe, analyse, and evaluate the vibrational data that was collected. Creo Simulate allowed FEA analysis of a human vertebra which enabled quantitative data to be obtained and thus compared to physical thresholds of the human body allowing a reasonable judgment to be made on the effects and safety of the excavator operator. The following subheadings discuss the details involved in this computational study.

4.3.1 Excel

The use of Microsoft Excel was highly beneficial as it allowed the collected data values to be tabulated from which critical values such as maximums, minimums, averages, and other relevant calculations could be calculated quickly and accurately. An alternative to Excel, MATLAB was considered as an option of computer program that would be suitable and capable of using and even may be a more advanced option. However, upon comparing the two programs it became apparent that Excel was the most appropriate option due being more proficient in the use of excel compared to MATLAB due to having more experience using Excel. Therefore, Excel was used for analysis, calculations, and sorting of data as this was determined to be the most efficient and effective option.

Upon completion of the data collection phase, all data points were copied and pasted from the Arduinos serial monitor directly into an excel spreadsheet. This provided the X, Y, and Z axial acceleration values in three separate columns. Before graphs could be created with this data, a column depicting the time of each data point had to be produced. To do this we refer back to the Arduino code where it was set to produce a new data point every 50 milliseconds, with this information a time column could be easily created in excel that starts at 0.05 seconds and increases by 0.05 for every data point.

Now having all the required data, graphs were created for each axis which presented the acceleration in g's on the Y axis and time in seconds on the X axis. The graphs for each axis were separated because when they were plotted together it was difficult to read and distinguish between them. For each axis a graph was produced for the total time of operation, further graphs were created that isolated the specific tasks that were performed. This was done to show a more detailed view of the vibration during these tasks thus allowing for an appropriate and detailed analysis.

A whole-body vibration calculator created in excel was downloaded from UK's Health and Safety Executive website [hse.gov.uk, 2022]. The calculator is used to determine the daily vibration exposures for each axis and thus the overall daily vibration exposure. To use the calculator the average vibration magnitudes are input into their designated location on the spreadsheet, then the exposure time in hours in its designated cell, for this case the exposure time was said to be eight hours as this is the standard time for a full-time employee. Once these values are inputted, the calculator returns a value for daily vibration exposure and highlights the cell in green, yellow, or red representing levels of safety, green being a safe limit, yellow for when action needs to be taken to oppose vibration, and red for values exceeding the exposure limit value.

4.3.2 Solid Modelling and Simulation

Solid modelling and simulation were included in the analysis for the project because it could add another aspect of investigation. Using a CAD software allowed for the material properties of a lumbar vertebrae to be assessed under the working conditions.

3D modelling software program CREO was used as the system to conduct this analysis as it was the program that was accessible and that was most experienced using. Upon observing and studying the shape and dimensions of a human vertebra it was learned that the shape is quite complex and intricate. To create this shape manually would take a considerable amount of time and would be difficult to achieve. For this reason, it was decided that the most appropriate option to generate a 3D model of the vertebrae was to download a model that had already been created by another individual or company. The model for the lumbar vertebrae was downloaded from the GradCAD.com community library where a model was found created by Daniel Robinson in 2018 by using CT scans and other medical equipment to scan the vertebrae and create a highly accurate 3D model. This model is pictured below in figure 4.7.

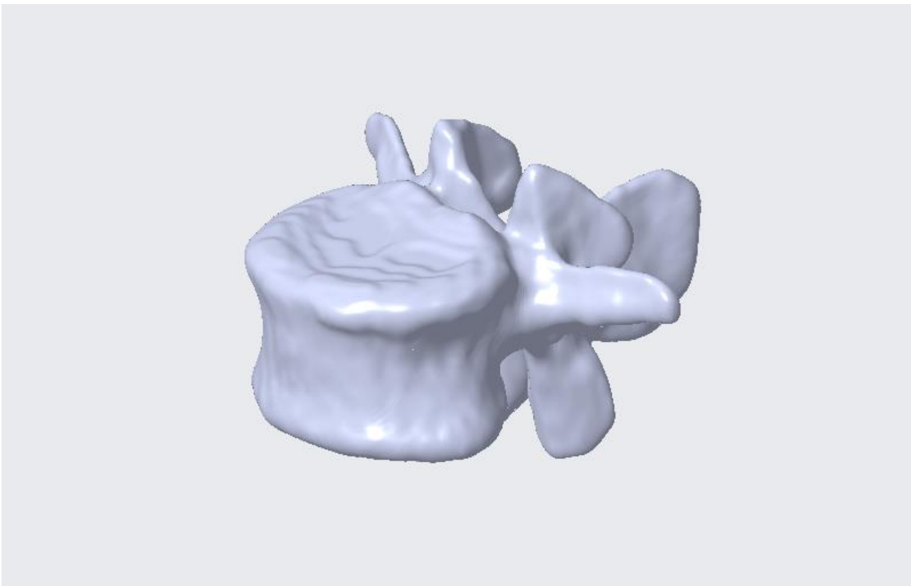


Figure 4.7: Imported model of human lumbar vertebra

Having downloaded the model, it was opened in CREO Parametric where a material could be assigned and some axes, mesh, and constrains could be set up. Bone is not a material listed in the materials library in CREO and so an alternative similar material had to be chosen or a customised material created to the properties of bone. Researching the properties of bone revealed limited available mechanical properties of the material with many of the values required to create a new material in CREO not being presented. This led to the research of bone alternatives and materials with similar properties to bone. A study by a student from the University of Newcastle revealed that polyurethane foam was the most preferable substitute for testing and analysing bone and joints. This information was very useful as rigid polyurethane foam is listed in the materials library in CREO and thus it was selected as the material to assign to the model.

The model was imported as a hollow quilt and in order to run a simulation analysis the model had to be solidified. Before the solidify tool within CREO was able to be used the model had to be repaired to close any and all gaps. To do this the import doctor tool was utilised which identifies and fixes any gaps or errors within the model. Having modified the model to fill all gaps or double edges/surfaces, the model was solidified. Now with a solid model constraints and loads could be applied. A displacement constraint was applied to the back side of the vertebral body as this was determined to be the most appropriate location because the spinal cord runs through here and the processes interlock.

Load constraints were added as forces on the top and bottom of the vertebra to simulate the forces of from the above vertebra pushing down and the equal and opposite force from below vertebra pushing up. The value used for this force was estimated from an average person's torso weight multiplied by the maximum acceleration determined from data collected from the Arduino. Once the loads were applied, constraints set, material assigned, and any other requirements were completed the analysis was run and the results were observed.

Chapter 5

Results and Analysis

5.1 Experimental Test Results

5.1.2 Vibrational Data Results

All the data values that were recorded by the accelerometer were imported into an excel spreadsheet with the values for each axis organised into separate columns. This resultant table is far too large to include its entirety within this report, so a short portion of the tables is included below. Before any calculations could be made the results had to be refined to achieve a resultant unit of m/s^2. This was done by firstly dividing by 100 and then multiplying by 9.81. Each set of results is shown below in tables 5.1, 5.2, and 5.3.

Table 5.1: Data as it came from the Arduino

Unaltered (g's)			
X	Y	Z	Time (sec)
16.02	24.29	100.78	0.05
16.24	24.78	100.76	0.1
11.23	24.22	97	0.15
11.69	23.66	98.78	0.2
15.11	24.88	101.37	0.25
13.16	24.22	99.32	0.3
10.99	24.19	98.39	0.35
15.45	24.37	102.69	0.4
15.58	24.56	102.03	0.45
10.77	23.73	99.54	0.5
11.87	23.95	99.51	0.55

Table 5.2: Values from table 5.1 divided by 100 to revert to realistic values

Divide by 100			
X	Y	Z	Time (sec)
0.1602	0.2429	1.0078	0.05
0.1624	0.2478	1.0076	0.1
0.1123	0.2422	0.97	0.15
0.1169	0.2366	0.9878	0.2
0.1511	0.2488	1.0137	0.25
0.1316	0.2422	0.9932	0.3
0.1099	0.2419	0.9839	0.35
0.1545	0.2437	1.0269	0.4
0.1558	0.2456	1.0203	0.45
0.1077	0.2373	0.9954	0.5
0.1187	0.2395	0.9951	0.55

Table 5.3: Acceleration values in required form (m/s^2), note that 9.81 was subtracted from the Z axis

m/s^2			
X	Y	Z	Time (sec)
1.571562	2.382849	0.076518	0.05
1.593144	2.430918	0.074556	0.1
1.101663	2.375982	-0.2943	0.15
1.146789	2.321046	-0.11968	0.2
1.482291	2.440728	0.134397	0.25
1.290996	2.375982	-0.06671	0.3
1.078119	2.373039	-0.15794	0.35
1.515645	2.390697	0.263889	0.4
1.528398	2.409336	0.199143	0.45
1.056537	2.327913	-0.04513	0.5
1.164447	2.349495	-0.04807	0.55

Using this refined and tabulated data, graphs were made depicting the vibration on each axis for the whole duration of data collection, for a period of time when the excavator was tracking, and for a period of time when the excavator was spreading and moving material. These resultant graphs are pictured in the figures below.

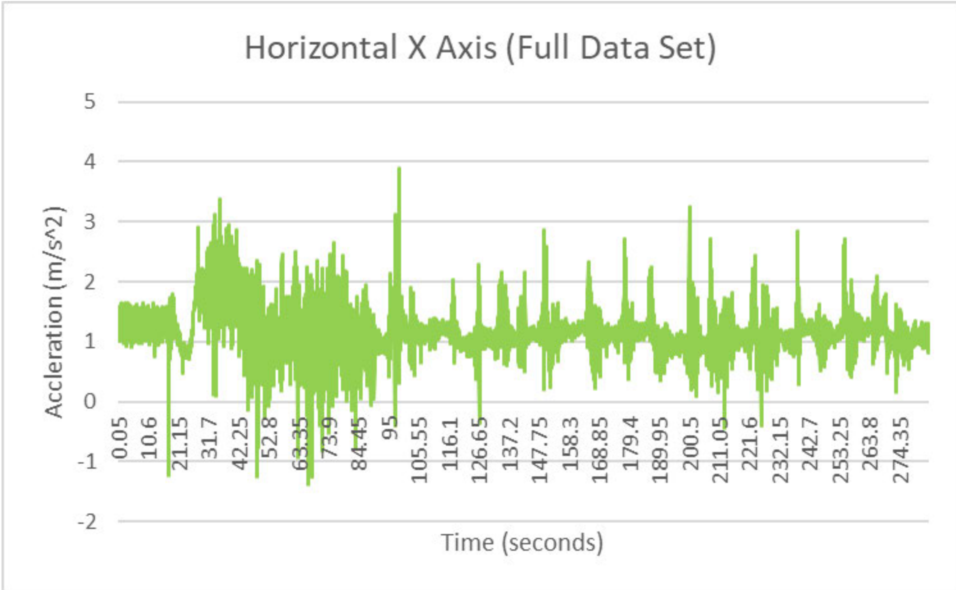


Figure 5.1: Vibration graph for whole data set on X axis

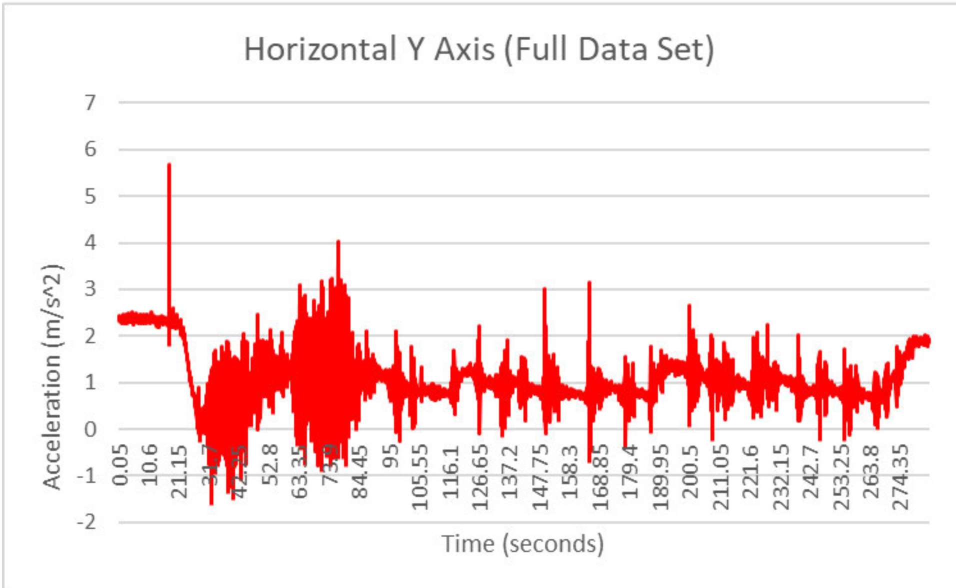


Figure 5.2: Vibration graph for whole data set on Y axis

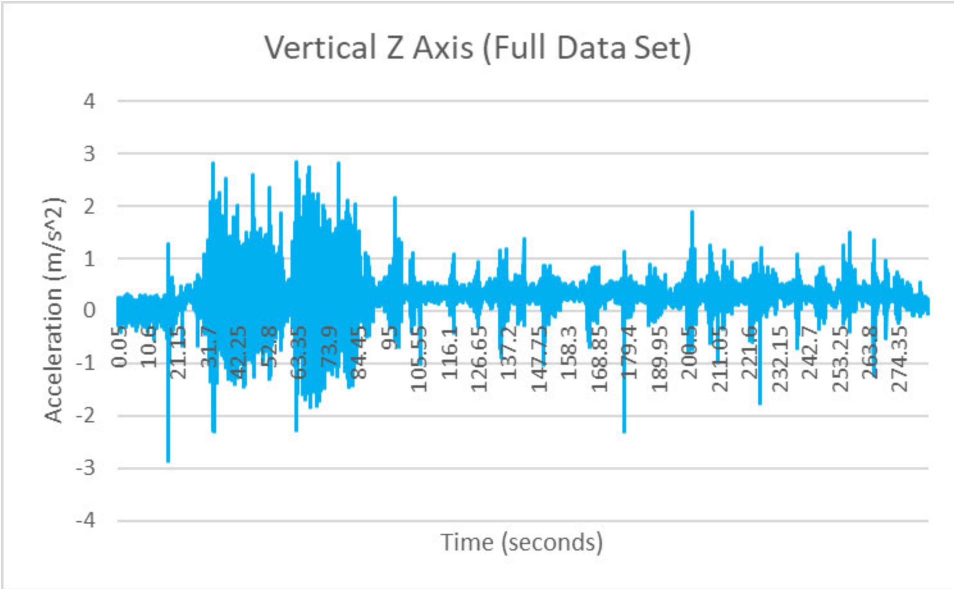


Figure 5.3: Vibration graph for whole data set on Z axis

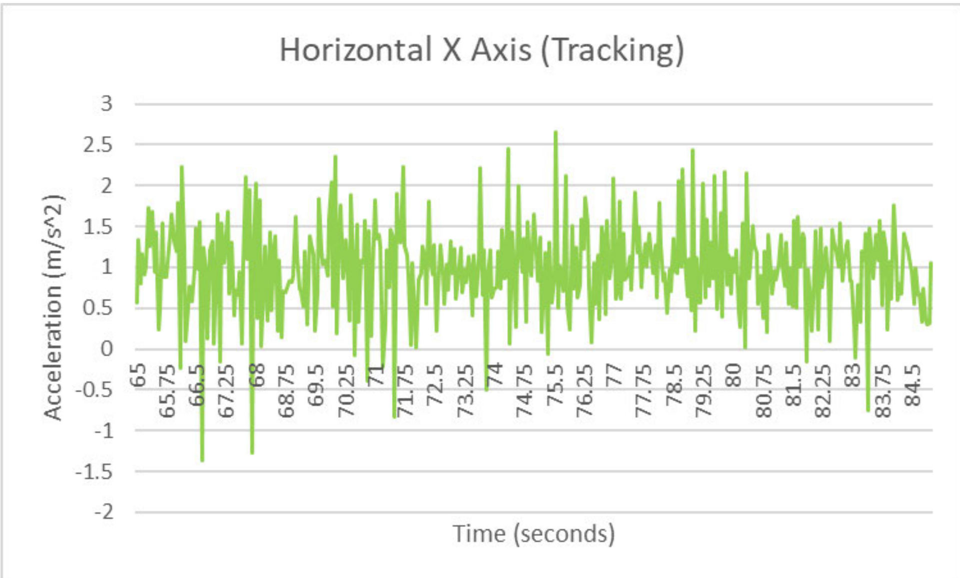


Figure 5.4: Vibration graph for X axis for a period of time when the excavator was tracking

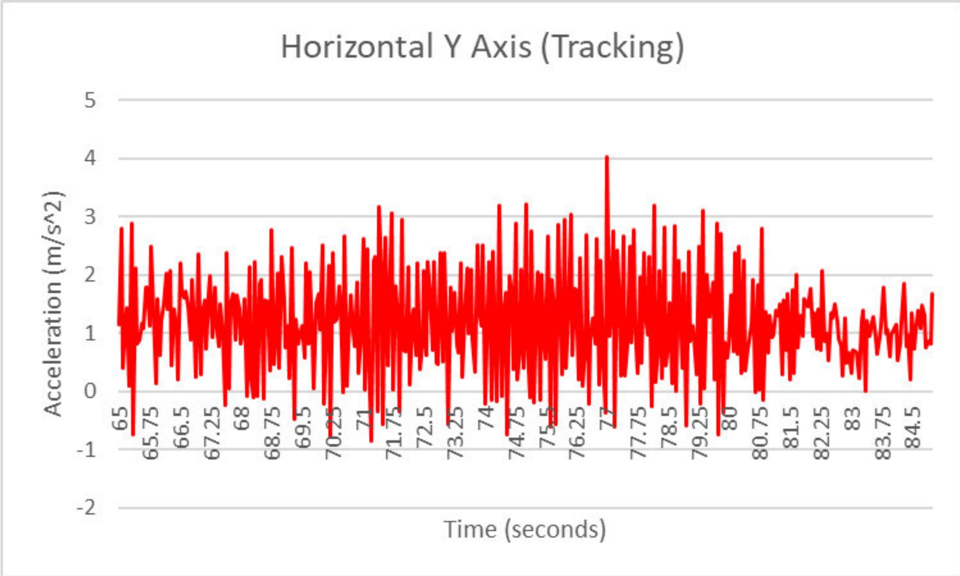


Figure 5.5: Vibration graph for Y axis for a period of time when the excavator was tracking

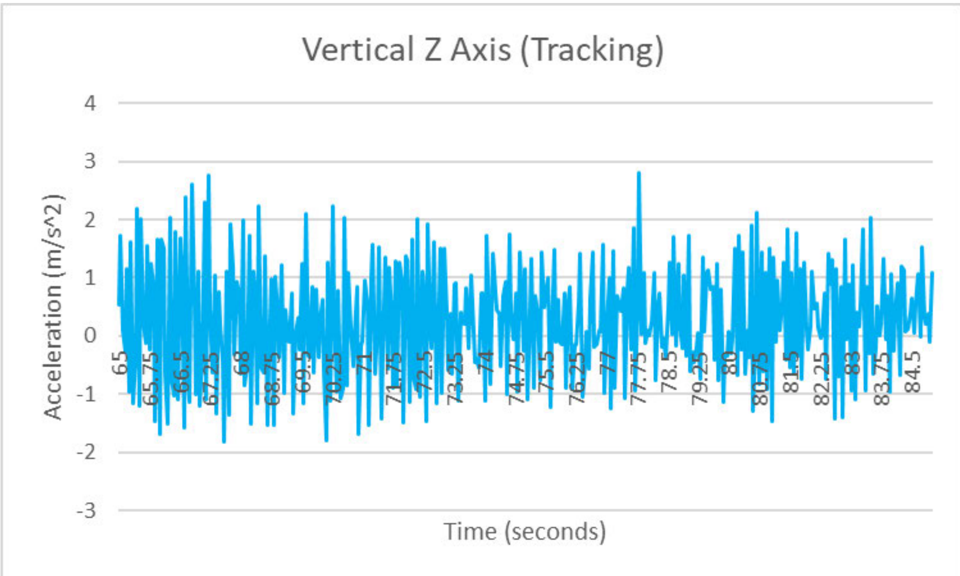


Figure 5.6: Vibration graph for Z axis for a period of time when the excavator was tracking

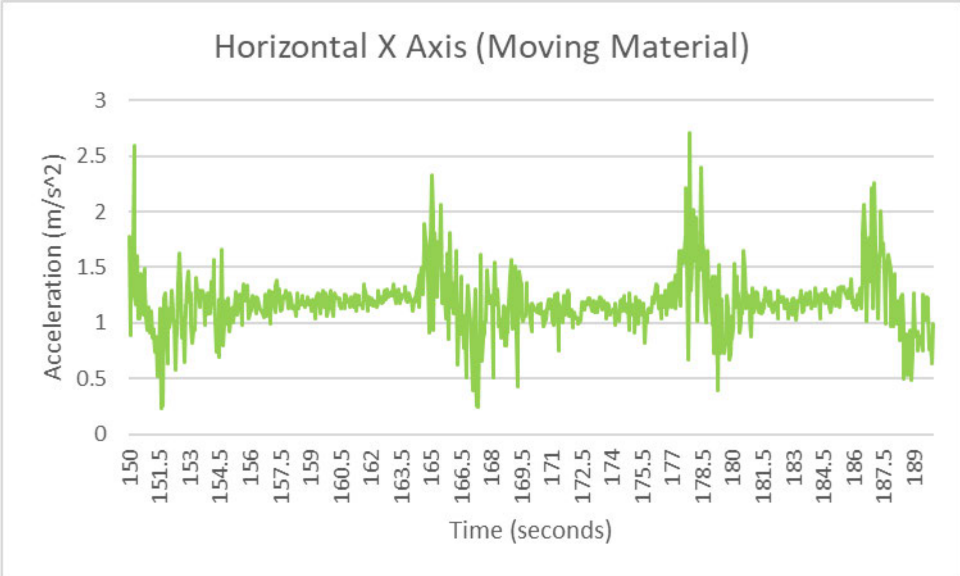


Figure 5.7: Vibration graph for X axis for a period of time when the excavator was moving material

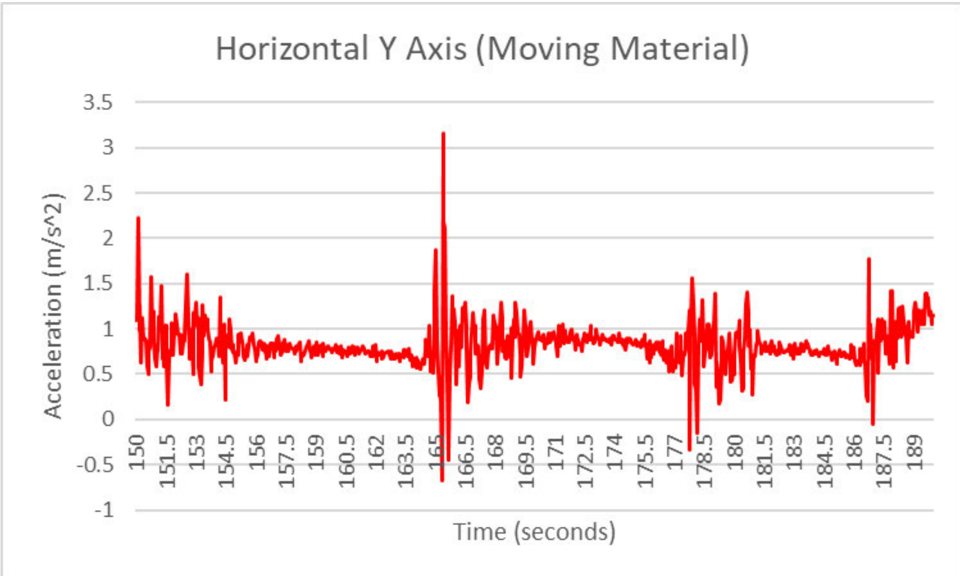


Figure 5.8: Vibration graph for Y axis for a period of time when the excavator was moving material

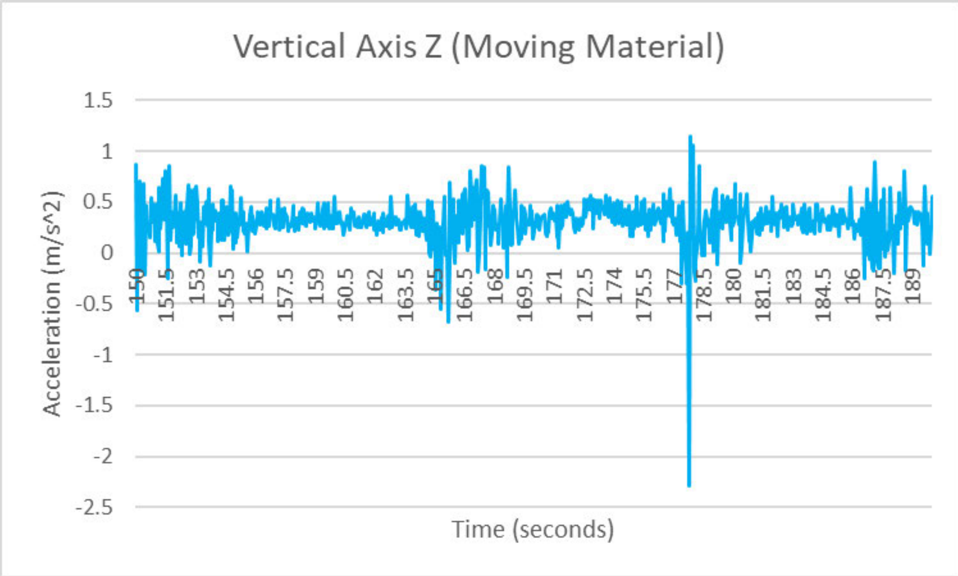


Figure 5.9: Vibration graph for Z axis for a period of time when the excavator was moving material

Average vibrational magnitudes were determined for each axis and put into a daily vibration exposure calculator to determine if the vibration experienced by the operator during an eight-hour day was within safe limits.

Table 5.4: Average acceleration for each axis in m/s^2

Averave Acceleration (m/s^2)		
X	Y	Z
1.158158	1.079023	0.275681

Table 5.5: Partial daily vibration exposure table highlighting if within safe limits

Partial Daily Vibration Exposures		
A(8) x-axis m/s² A(8)	A(8) y-axis m/s² A(8)	A(8) z-axis m/s² A(8)
1.62	1.51	0.28
Total A(8) exposures		
1.62	1.51	0.28
Daily Vibration exposure, m/s² A(8)		
1.62		
Colour key		
Less than EAV (0.5 m/s² A(8)):		
EAV (0.5 m/s² A(8)) or higher:		
ELV (1.15 m/s² A(8)) or higher:		

5.1.3 Analysis of Results

Numerical data provided by the Arduino was converted from g's to m/s^2 as this was the units required for further vibrational analysis and because we are more familiar with values in m/s^2 rather than g's. 9.81 was subtracted from the Z axis to eliminate the acceleration due to gravity which allowed acceleration solely from operation of the excavator to be collected. The starting data points for the X and Y acceleration should have theoretically been zero, however, this was not the case as seen in table 5.3. This was a result of the topography of the testing site, the area of land where the excavator was operating was slightly inclined and thus the horizontal axis recorded some acceleration due to gravity. This same issue was true for the Z axis however since 9.81 is an easy constant this was still the value factored out of the data set as it was decided a reasonable number would still be attained. The X and Y axis on the other hand was too difficult to determine a value to factor out due to having more variables effecting the recorded numbers, and so they were kept the same. Although this did affect the results, differences in each axis and their vibration wave forms were still able be determined and compared relative to each other.

The use of computational methods to analyse the experimental data allowed for visualisation of the vibrations present throughout the course of the testing period thought the creation of graphs. Upon observation the resultant graphs, it became clear that the vibrations produced during the operation of an excavator greatly differ depending on what action is being performed. Due to the nature of excavator operation, this determination was expected, and the results confirmed the hypothesis. Three sets of graphs were presented; full data set, tracking, and moving material, this was done to allow for a more detailed analysis of the actions performed.

The first three graphs presented show the vibrational data for the full duration of testing. The first third of the graph is when the excavator was tracking, and the last two thirds of the graph is when the excavator was mostly stationary while moving and spreading material. Comparing the graphs for the X, Y, and Z directions it was observed that a similar wave form pattern was experienced in all axial directions with slight differences in magnitude. It was determined that overall, the X axis experienced the most prominent vibration, followed by the Y Axis, and finally the Z axis with the least intense vibration.

Taking a look at the next set of graphs titled "Tracking" we see the vibration for a period of time when the excavator was tracking. Again, we see very similar wave form patterns across the three axes. Comparing the three graphs it is evident that the X axis experiences less frequent vibrations than the Y and Z axes. This is most likely due to the jerking motion that occurs along the X axis when the excavator is moving forwards. As for the magnitudes of vibrations while tracking, all axes were quite similar ranging from zero to two and a half with the X axis having a slightly larger range compared to the Y and Z.

The final three graphs presented above provide vibration information for when the excavator was mostly stationary while moving and spreading material. The vibrational wave form generated here is much less violent than what was observed when tracking which was expected. Looking at the graphs for each axis we can see an almost cyclic pattern where there is a spike in vibration roughly every ten seconds. This pattern was caused by a flicking motion the operator performed at the end of each extension of the arm to through material under the excavator. The low vibration areas in between the spikes are because the operator moves gently and steadily while spreading the material which obviously generates minimal vibration.

Average vibration values were calculated over the whole duration of testing which were then used to calculate the daily vibration exposure value which tells us whether the levels of vibration are within safe limits. Once the values were inputted into the calculator in excel the exposure values were generated. The downloaded calculator had a key that distinguished if the resultant exposure values were within the safe limits, the results are pictured above in table 5.5. The exposure value for the Z axis is green, indicating that the vibration on the axis is within the safest limit. The X and Y axes returned a value highlighted in red meaning they are above the maximum exposure limit and control should be put in place to ensure this value is within the safe limits. This result, however, is not accurate due to the angle offset of the excavator on the ground that as explained above. To overcome come this a constant could be factored out of the data set however, due to the constantly changing angle of the ground a constant value could not be appropriately determined. This issue is further explained in chapter six, the discussion.

5.2 Computational Results

5.2.1 Simulation Results

CREO simulate was used to analyse the displacement, stresses, and strains within the human vertebra as a result of the forces acting on the component. These results are shown below as pictures from the CREO Simulate results window.

Figure 5.10: Max principal stress model

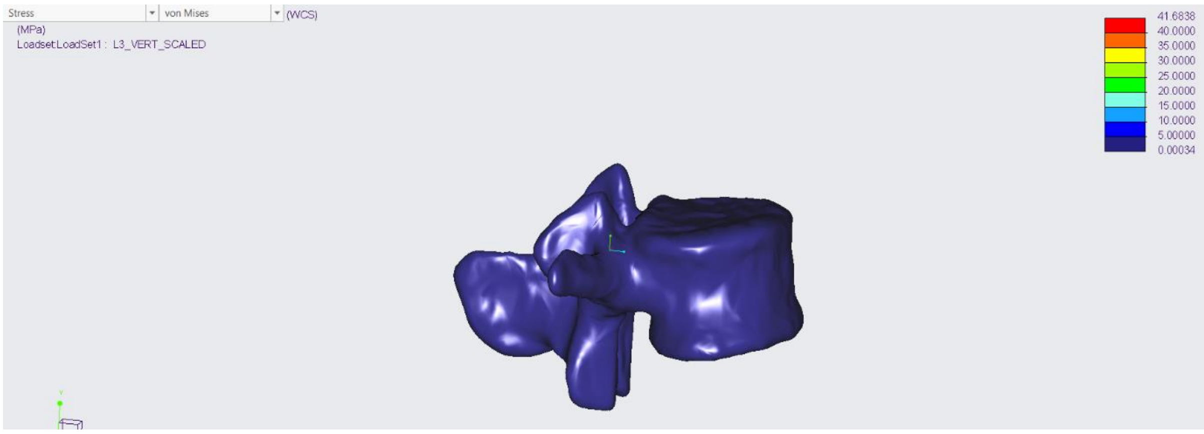


Figure 5.11: Von Mises stress model

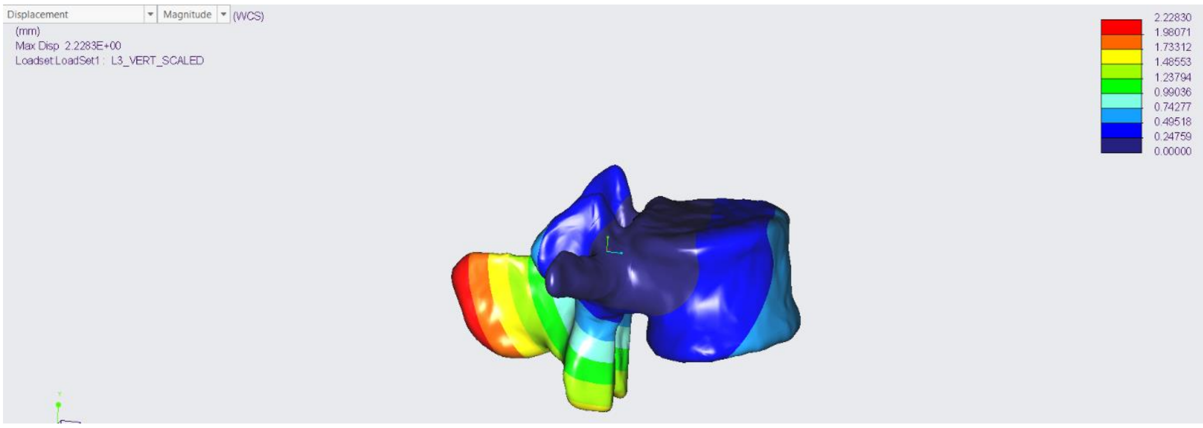


Figure 5.12: Displacement magnitude of model

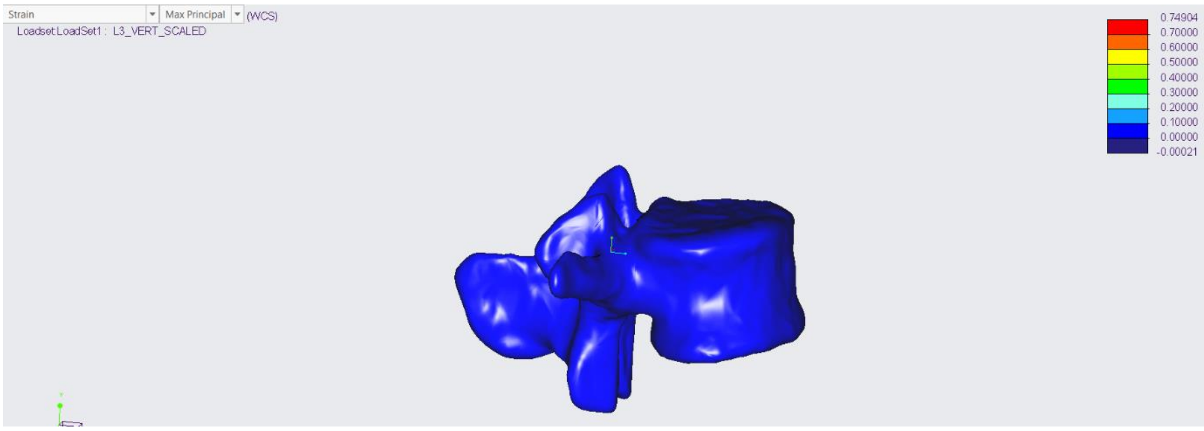


Figure 5.13: Max principal strain of model

5.2.2 Analysis of Results

The results for max principal stress and Von Mises stress show a solid colour throughout the whole model, this suggests that the forces acting on the vertebra will not cause much stress to the component based off the material properties. This was not the expected outcome as it was thought that different areas of the model would show different levels of stress. The results for displacement show the greatest displacement occurs at the rear of the vertebra on the protruding process and gradually decreases towards the front of the body to very minimal displacement. The final model presented from the simulation results is the max principal strain which shows the model a solid blue indicating that there is very minimal strain.

Chapter 6

Discussion

6.1 Discussion of Results

Unfortunately, as stated in the preceding section, the testing and data collection did not produce accurate results. This was due to several variables that both not completely considered and also unavoidable, this section of the dissertation will discuss these issues in detail.

Vibration control in heavy machinery is an aspect of the engineering design process that would definitely be considered and worked on by machine manufacturers. The aim of this project was not to determine the vibration controls required but rather to investigate if the vibration controls used in an excavator are sufficient and serve the purpose they are implemented for. This topic was chosen due to reports of many machine operators suffering from back and joint pain, which may suggest that the vibration controls are not protecting the operators from the full effects of whole-body vibration.

The device used to measure the changes in vibration, the MPU6050, measures vibration along the X, Y, and Z axes. For this sensor to measure vibration to accurately weighted magnitudes the sensor has to be perfectly level with the inbuilt axes of the sensor. Correct orientation of the sensor should produce acceleration values of zero on the X and Y axes and 9.81 on the Z axis when stationary. If, however the sensor is not aligned correctly to these axes the returned values will be offset according to the angle offset from the normal of the axes. This factor had an effect on the results from testing because the area of ground where the excavator was located had a changing gradient which ultimately offset the values for each axis throughout the duration of the data collection period by varying values depending on the position of the excavator. Determining the value of offset proved to be near impossible given the resources and data available. The Z axis was able to be rectified to some degree by factoring out the acceleration due to gravity as this is an easy constant, this produced a resultant set of values that was relatively close to what was expected however due to the gradient of the ground creating an offset from the perfect vertical direction the results are still not accurate. The X and Y axes were much harder to find a constant value to factor out due to forwards acceleration of the excavator and greater vibration in these directions. The results for the X and Y axes were not factored by a value or multiple values to attempt to improve the results as a value to factor out could not be determined, this is why in the above results for the X and Y axes exceed the maximum level of vibration exposure.

Since discovering this issue during the compilation and analysis of the collected data, several possible solutions to this issue were realised. However, all solutions required the data collection phase to be completed again and due to the location of the excavator being in Coffs Harbour, a roughly five-and-a-half-hour travel, this was not an option due to the limited time remaining until the due date for the dissertation and the cost of the trip would've been greater than what was willing to be spent for the purpose of the project.

The firsts option to resolve the error in results was to collect the data again and take more notice and record the variables that had now been identified. This would include measuring the gradient of the slope the excavator was working on, this would allow for a manual calculation to determine the angle offset from the normal and thus calculate the resultant factored vibration. To add another level of security to the angle offset, the gyroscope within the MPU6050 could be utilised. The gyroscope in the MPU6050 measures angular acceleration and thus if this function of the senor is used the exact angle that the excavator is tilted could be determined and the factored vibration could be calculated. The coding required to include the gyroscopes data was not included in the Arduino code because this aspect was not considered due to regretfully overlooking these variables as an issue.

Arduino was used to collect data as it was the cheapest option by a considerable amount as well as being an easy-to-use system. Basics of Arduino operation and coding had been taught throughout the course of the mechanical engineering degree and so an intermediate knowledge of the Arduino was already known making the process of using and collecting desired data was far easier than learning new methods. Alternatively, to Arduino several other methods of gathering vibrational data were investigated such as advanced vibration sensors and a WBV monitor. These options were much more expensive and more difficult to obtain than the Arduino and its components especially considering the Arduino was already in possession. If funding was not an issue for this project these devices would've been purchased and utilised as they would produce results of higher accuracy and quality allowing for significant conclusions to be made.

Data was collected from the excavator over a period of roughly ten minutes. This was not the original plan but due to issues that arose shortly before the trip to Coffs Harbour was scheduled, this time frame was the most appropriate considering the changes. Initially, a SD card reader and SD card was purchased as an attachment for the Arduino which would have the purpose of storing the data captured by the MPU6050. The plan was to include the SD card reader and SD card into the Arduino apparatus and write a code to print the data collected by the MPU6050 onto the SD card. This would've allowed for remote data collection meaning once the device was set up in the excavator it could be left running for the whole day or for as long of a during as desired. This idea method was not implemented due to issues with coding the SD card reader into the Arduino program. Several different codes were used in an effort to write data to the SD card and store it but after many attempts and troubleshooting the desired outcome was never achieved. With limited time left to get the SD card reader working correctly the decision was made to not use the SD card as a means to store the vibrational data from the excavator to ensure that the project could be finished by the due date. The easiest alternative for saving the data was to plug the Arduino into a laptop sitting on the floor of the cab of the excavator and once adequate data had been collected copy and paste the data set from the serial monitor into a text file. This decision impacted the allowable time that data could be collected because the laptop was inconvenient for the operator to work around and thus it was decided that the time for data collection should be kept as short as possible while still allowing enough time to gather sufficient data. Collecting data over a longer period of time would've been preferred however, the actions performed during the ten minutes of operation reflected the most common actions that an excavator would perform during a typical working day and thus a simple evaluation and analysis could be conducted.

CREO Parametric and Simulate was used as the 3D modelling software because it is the program that was taught at university and thus the program, I had the most experience with. This project did not necessarily require 3D modelling or simulation, but the decision was made to include this form of analysis to add an extra aspect of investigation. Modelling the lumbar vertebra proved to be quite difficult due to the complex shape of the component. To save time a model of a vertebra was downloaded from GradCAD.com where someone had used medical scanners to create a highly detailed and accurate model of the lumber vertebra. Doing this allowed for a more accurate and detailed computational analysis. Creating the model, myself would've been a good opportunity to develop my 3D modelling and computational simulation skills, however, with the time restraint on the project there was simply not enough time to model the part myself as it would've required learning new methods, techniques, skills, and outsourcing of equipment.

The simulation results did not produce the outcomes that were expected and is assumed that something was not done correctly in the process to achieve the desired results. It is thought that the displacement constraint applied may be the cause for the lack of results as it was quite difficult the define the true constraints of a human vertebrae and so the constraint was placed on the back side of the vertebral body. The material assigned to the model may also have caused discrepancies in results since it was not bone but a similar material as discovered by the University of Newcastle. Overall, the results from simulations were not as useful as expected nor as accurate which is a result of lack of skill and experience using the software.

6.2 Reflection

I chose the topic out of genuine interest as it was an issue that had personal relevance and allowed me to use knowledge and skills, I was taught throughout the course of my mechanical engineering degree. Throughout the progression of this investigation, it proved to be much larger than first anticipated. When researching and learning more about the topic I realised that this investigation could include much more information that was I first planned for, and if a truly comprehensive and detailed study were to be completed the project would require more time and funding that was available. To keep the project on track to be completed by the due date many sections and details had to cut short to achieve this. Many lessons were leant while completing this project such as the importance of time management, having a strong understanding of the fundamental engineering topics, professional writing, and many more aspects of engineering that has opened my eyes and prepared me for the workplace after graduation.

6.3 How Can These Results Be Used in Industry

Results obtained from this particular study unfortunately will not be useful to any machine manufacturing industries due to unforeseen errors in the methodology and results. If, however, this project was to be performed again given more time, resources, and utilising the lessons learned, this topic could produce major discoveries regarding the safety of machine operators. If this issue is looked into on a larger more professional scale, there is a high possibility of discovering flaws in the current vibration control systems that could lead to the redesign of these systems to hopefully improve the safety of heavy machinery operation. Improving the safety of machine operation would allow machine operators to have a greater quality of life by decreasing the pain experienced by these individuals and the consequences that come with it such as, surgeries, time off work, and immobility. The general consciences of the project topic is a particular portion of the broader idea of safety of machine operators. Further study of this topic would encourage other aspects of machine operation to be studied such as ergonomics which could lead to a safer and overall greater operating experience.

Chapter 7

Conclusion

7.1 Conclusions

The effects of vibration on the operator of an excavator was the focus of this research project. The background information, literature review, and following experimental and computational aspects of this study allowed for a strong and thorough knowledge and understanding of the topic. It was found that prominent vibrations are present in the X, Y, and Z axes during all operating actions. Unfortunately, due to errors in the methodology the results found were inaccurate and thus conclusions could not be presented.

From research it was discovered that the severity of the effects due to vibration on a machine operator greatly varies depending on the posture of the operator, magnitude of vibration, age of the machine and the operator, and daily and long-term exposure to WBV. Reviewing previous literature on relevant topics highlighted these variables and the importance they have in understanding how whole-body vibration effects machine operators.

Vibrational data was collected in the X, Y, and Z axes from a 24 tonne Komatsu excavator during an operating period of ten minutes using an Arduino Uno and MPU6050. The data collection process was successful however, unfortunately, this data was not accurate due to the changing slope of the ground offsetting the MPU6050 from its normal axis and thus relaying this offset to the resultant data points measured by the device due to acceleration from gravity. This issue could have been resolved by repeating the data collection phase and programming the Arduino to measure angular acceleration however, due to limited time and the location of the excavator this was simply not possible.

Although the data points were not accurate due to the angle offset, graphs created for each axis were still able to represent the vibrational patterns that occur during different operating tasks. This is important because it allows judgements and evaluations to be made for machines in different industries and apply vibration controls accordingly.

Computational analysis was performed in CREO Simulate that produced observational and quantitative data for stress, strain, and displacement. However, these results are not reliable and did not return expected outcomes, this was a results of user error and inexperience. This is a component of the project that requires further work to achieve desired and useful results.

The initial aim of this project was to investigate the effects whole body vibration has on excavator operators. A correct methodology was implemented to gather the data required to determine the effects vibration has on an excavator operator. However, unfortunately, no solid conclusions could be determined from this study due to the errors in results and not adequate time to correct these errors. Through research of past literature, effects caused by whole-body vibration were discovered for other types of heavy machinery and variables that influence the severity of the subsequent effects.

7.2 Further Work

Since errors were made in this project, further work would need to be undertaken in order to achieve conclusive results. It would be ideal for this investigation to be repeated with the lessons learnt and knowledge that was inherited from this project. Machine operators do experience negative health effects due to whole body vibration as discussed and highlighted throughout the text. If further work can produce convincing results, it could lead to the redesign of vibration control system in heavy machinery thus improving the lives of machine operators.

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Appendix

Appendix A – Project Specifications

ENG4111/4112 Research Project

Project Specification

For: Brad Chambers

Title: Vibration analysis of an excavator to investigate the effects on the operator

Major: Mechanical Engineering

Supervisors: Khalid Saleh

Enrollment: ENG4111 – EXT S1, 2021

ENG4112 – EXT S2, 2021

Project Aim: To gather, model and simulate vibrational data from an excavator to investigate the effects whole body vibration has on the human body.

Programme: Version 1, 15^{th} March 2021

1. Conduct background research on the effects of vibration on the body and the limitations the body can withstand. Also, research health problems and injuries related to the operation of machinery and how common it is.
2. Conduct initial research on sensors and gauges to determine and identify what may be necessary and appropriate for data collection. Also determine areas of the excavator to mount the sensors to collect most accurate data.
3. Collect and record data from the operation of the excavator
4. Create graphs and tables from the data collected
5. Generate CAD models of the wear part and perform FEA
6. Evaluate and compare the results from the FEA and generate a judgement on the effects to the excavator operator
7. Suggest solutions or methods to reduce any effects on the operator

If time and resource permit:

8. Conduct research and testing on other types of machinery

Appendix B – Project Resources

- Access to a personal computer with relevant software installed for research, document processing, and data analysis, such as Microsoft office and CREO.
- Arduino Uno, MPU6050, SD card reader & SD card, jumper wires, Arduino IDE
- Access to 24 tonne excavator and job site
- Vehicle to travel to location of excavator
- Internet access & USQ internet access

Appendix C – Project Plan

	Semester 1 - ENG4111																			Semester 2 - ENG4112															
Task	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
Phase 1 - Project Preperation																																			
Project approval																																			
Communications with supervisor																																			
Background information																																			
Literature review																																			
Methodology																																			
Phase 2 - Data Collection																																			
Purchase sensors																																			
Code Arduino																																			
Collect data																																			
Compile data/create grapghs & tables																																			
Phase 3 - Modelling																																			
Create CAD model																																			
Transfer data to programs																																			
Run FEA analysis																																			
Phase 4 - Analysis & evluation of results																																			
Observe/analyse results from FEA																																			
Assess results with standards/limits																																			
Suggest methods to reduce effects																																			
Phase 5 - Dissertaion																																			
Draft																																			
Profesional practice 2																																			
Completion																																			

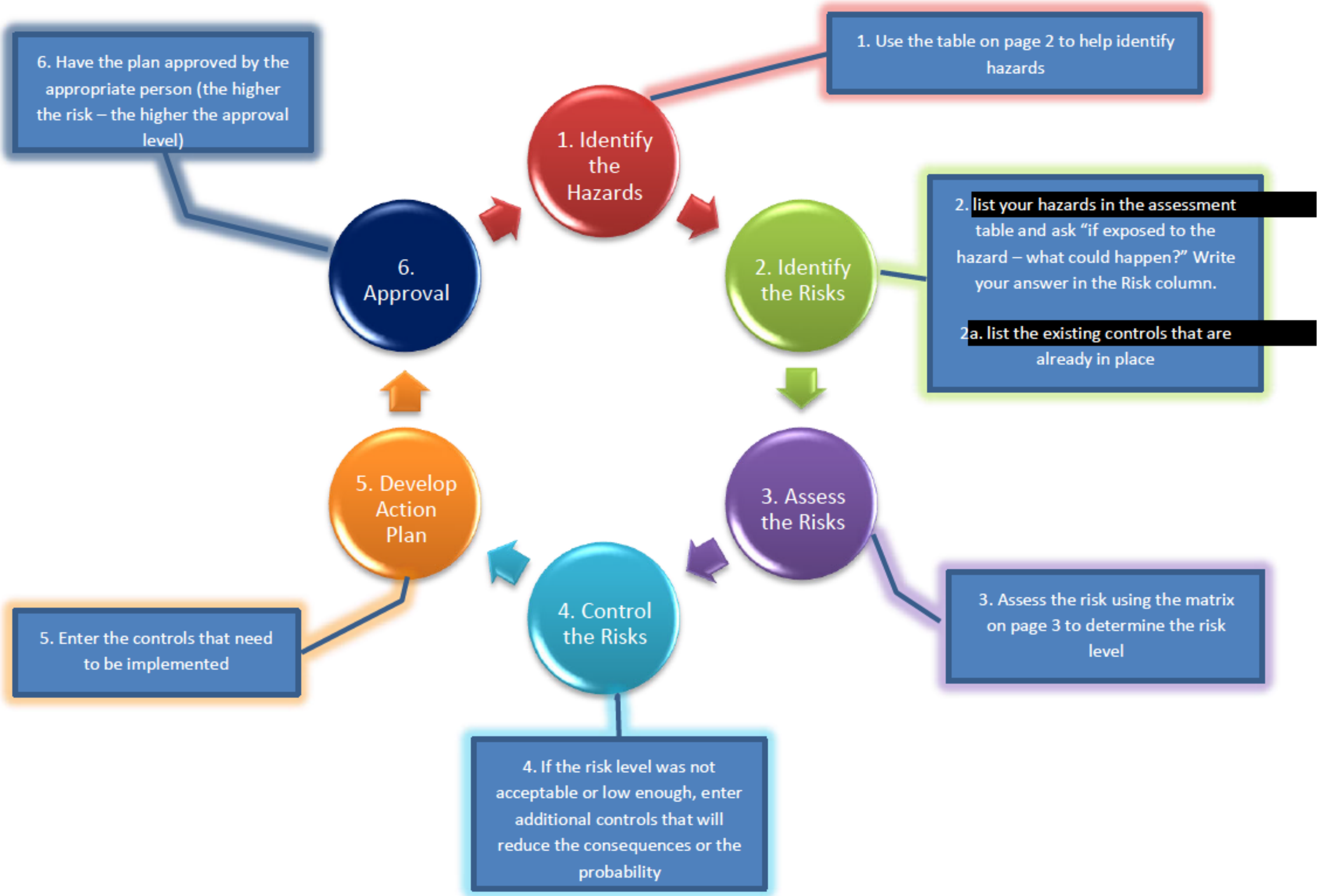
University of Southern Queensland

Appendix D – Risk Assessment

Generic Risk Management Plan

Workplace (Division/Faculty/Section): Mechanical engineering		
Assessment No (if applicable):	Assessment Date: 13/10/2022	Review Date: (5 years maximum) / /
Context: What is being assessed? Describe the item, job, process, work arrangement, event etc: Eng4111 Thesis Research Project, vibration analysis of an excavator to investigate the effects on the operator. Need to be onsite the measure vibration on an excavator.		
Assessment Team – who is conducting the assessment?		
Assessor(s): Brad Chambers Others consulted: (eg elected health and safety representative, other personnel exposed to risks)		

The Risk Management Process



Step 1 - Identify the hazards (use this table to help identify hazards then list all hazards in the risk table)		
General Work Environment		
☒ Sun exposure	☐ Water (creek, river, beach, dam)	☐ Sound / Noise
☐ Animals / Insects	☐ Storms / Weather/Wind/Lightning	☐ Temperature (heat, cold)
☒ Air Quality	☐ Lighting	☒ Uneven Walking Surface
☒ Trip Hazards	☐ Confined Spaces	☒ Restricted access/egress
☐ Pressure (Diving/Altitude)	☐ Smoke	☐
Other/Details:		
Machinery, Plant and Equipment		
☐ Machinery (fixed plant)	☒ Machinery (portable)	☐ Hand tools
☐ Laser (Class 2 or above)	☐ Elevated work platforms	☐ Traffic Control
☐ Non-powered equipment	☐ Pressure Vessel	☐ Electrical
☒ Vibration	☐ Moving Parts	☐ Acoustic/Noise
☒ Vehicles	☐ Trailers	☐ Hand tools
Other/Details:		
Manual Tasks / Ergonomics		
☐ Manual tasks (repetitive, heavy)	☐ Working at heights	☐ Restricted space
☒ Vibration	☐ Lifting Carrying	☐ Pushing/pulling
☐ Reaching/Overstretching	☐ Repetitive Movement	☐ Bending
☒ Eye strain	☐ Machinery (portable)	☐ Hand tools
Other/Details:		
Biological (e.g. hygiene, disease, infection)		
☐ Human tissue/fluids	☐ Virus / Disease	☐ Food handling
☐ Microbiological	☐ Animal tissue/fluids	☐ Allergenic
Other/Details:		
Chemicals Note: Refer to the label and Safety Data Sheet (SDS) for the classification and management of all chemicals.		
☐ Non-hazardous chemical(s)	☐ 'Hazardous' chemical (Refer to a completed hazardous chemical risk assessment)	
☐ Engineered nanoparticles	☐ Explosives	☐ Gas Cylinders
Name of chemical(s) / Details:		
Critical Incident – resulting in:		
☐ Lockdown	☐ Evacuation	☐ Disruption
☐ Public Image/Adverse Media Issue	☐ Violence	☐ Environmental Issue
Other/Details:		
Radiation		
☐ Ionising radiation	☐ Ultraviolet (UV) radiation	☐ Radio frequency/microwave
☐ infrared (IR) radiation	☐ Laser (class 2 or above)	☐
Other/Details:		
Energy Systems – incident / issues involving:		
☐ Electricity (incl. Mains and Solar)	☐ LPG Gas	☐ Gas / Pressurised containers
Other/Details:		
Facilities / Built Environment		
☐ Buildings and fixtures	☐ Driveway / Paths	☐ Workshops / Work rooms
☐ Playground equipment	☐ Furniture	☐ Swimming pool
Other/Details:		
People issues		
☐ Students	☐ Staff	☐ Visitors / Others
☐ Physical	☐ Psychological / Stress	☐ Contractors
☒ Fatigue	☐ Workload	☐ Organisational Change
☐ Workplace Violence/Bullying	☐ Inexperienced/new personnel	☐
Other/Details:		

Step 1 (cont) Other Hazards / Details (enter other hazards not identified on the table)
Driving long distance

Risk Matrix

Eg 1. Enter Consequence

Eg 2. Enter Probability

Eg 3. Find Action

	Consequence				
Probability	**Insignificant** No Injury 0-$5K	**Minor** First Aid $5K-$50K	**Moderate** Med Treatment $50K-$100K	**Major** Serious Injuries $100K-$250K	**Catastrophic** Death More than $250K
Almost Certain 1 in 2	M	H	E	E	E
Likely 1 in 100	M	H	H	E	E
Possible 1 in 1000	L	M	H	H	H
Unlikely 1 in 10 000	L	L	M	M	M
Rare 1 in 1 000 000	L	L	L	L	L
Recommended Action Guide					
E=Extreme Risk – Task ***MUST NOT*** proceed					
H=High Risk – Special Procedures Required (See USQSafe)					
M=Moderate Risk – Risk Management Plan/Work Method Statement Required					
L=Low Risk – Use Routine Procedures					

Risk register and Analysis

Step 1 (cont)	Step 2	Step 2a	Step 3			Step 4				
Hazards: From step 1 or more if identified	**The Risk:** What can happen if exposed to the hazard with existing controls in place?	**Existing Controls:** What are the existing controls that are already in place?	**Risk Assessment:** (use the Risk Matrix on p3) Consequence x Probability = Risk Level			**Additional controls:** Enter additional controls if required to reduce the risk level	**Risk assessment with additional controls:** (use the Risk Matrix on p3 – has the consequence or probability changed?)			Controls Implemented? Yes/No
			Consequence	Probability	Risk Level		Consequence	Probability	Risk Level	
Example										
Working in temperatures over 35º C	Heat stress/heat stroke/exhaustion leading to serious personal injury/death	Regular breaks, chilled water available, loose clothing, fatigue management policy.	catastrophic	possible	high	temporary shade shelters, essential tasks only, close supervision, buddy system	catastrophic	unlikely	mod	Yes
Sun exposure	Sun burn	Sun block	Minor	Unlikely	Low	long sun protective clothing	Minor	Rare	Low	Yes
Air quality	Coughing, lung irritation	outside well-ventilated area	Minor	Unlikely	Low	face mask	Minor	Unlikely	Low	No
Trip hazards	Fall and injury self	safety fences around open pits and trip hazards	Moderate	Unlikely	Low	Not required	Select a consequence	Select a probability	Select a Risk Level	Yes or No
Uneven walking surface	Fall and injury self	take caution when on job site, wear appropriate shoes	Minor	Unlikely	Low	Not required	Select a consequence	Select a probability	Select a Risk Level	Yes or No
Restricted access	Get in trouble by site supervisor	contacted site supervisor about my presence.	Minor	Rare	Low	Not required	Select a consequence	Select a probability	Select a Risk Level	Yes or No
Vibration	fatigue, aches and pains	regular breaks	Minor	Unlikely	Low	Not required	Select a consequence	Select a probability	Select a Risk Level	Yes or No
Vehicles	Serious personal injury/death	high awareness, highly visible clothing	Major	Unlikely	Moderate	Not required	Select a consequence	Select a probability	Select a Risk Level	Yes or No
Machinery	Serious personal injury/death	high awareness, highly visible clothing, make presence known	Major	Unlikely	Moderate	Not required	Select a consequence	Select a probability	Select a Risk Level	Yes or No
Eye Strain	Sore eyes, headaches, nauseous	Regular breaks, appropriate distance from screen	Minor	Unlikely	Low	Not required	Select a consequence	Select a probability	Select a Risk Level	Yes or No
Driving long distance	Fatigue, tiredness, serious personal injury/death	Regular breaks, high awareness,	Major	Unlikely	Moderate	have mulitple drivers and swap when needed.	Moderate	Unlikely	Moderate	Yes
			Select a consequence	Select a probability	Select a Risk Level		Select a consequence	Select a probability	Select a Risk Level	Yes or No

Step 6 – Approval		
Drafter's Comments: All risks have controls in place		
Drafter Details:		
Name: Brad Chambers	Signature: Bradch	**Date**: 03/09/2022
Assessment Approval: (Extreme or High = VC, Moderate = Cat 4 delegate or above, Low = Manager/Supervisor) *I am satisfied that the risks are as low as reasonably practicable and that the resources required will be provided.*		
Name: Khalid Saleh	Signature: Khalid Saleh	**Date**: 11/10/2022
Position Title: Lecturer		

Appendix E – Arduino Code

vibrationsensor

```
// I2Cdev and MPU6050 must be installed as libraries, or else the .cpp/.h files
// for both classes must be in the include path of your project
#include "I2Cdev.h"
#include "MPU6050.h"


MPU6050 accelgyro;
const int chipselect = 4;
int16_t ax, ay, az;
int16_t gx, gy, gz;

#define LED_PIN 13
bool blinkState = false;

#define GZ_OFFSET -140
#define GYRO_SCALE 0.0076335877862595
#define ACCEL_SCALE 0.00006103515625

void setup() {
  // put your setup code here, to run once:

 // initialize serial communication
    // (38400 chosen because it works as well at 8MHz as it does at 16MHz, but
    // it's really up to you depending on your project)
    Serial.begin(38400);

    // initialize device
    Serial.println("Initializing I2C devices...");
    accelgyro.initialize();
```

```
  //**************************************************************************
//Set sensitivity  below. Be sure to make sure the GYRO_GAIN above matches.
//
//  Get full-scale gyroscope range.
//  The FS_SEL parameter allows setting the full-scale range of the gyro sensors,
//  as described in the table below.
//
//  <pre>
//  0 = +/- 250 degrees/sec
//  1 = +/- 500 degrees/sec
//  2 = +/- 1000 degrees/sec
//  3 = +/- 2000 degrees/sec
//

  accelgyro.setFullScaleGyroRange(0); //set range FS_SEL to 0 currently.

// AFS_SEL=0 ±2 g
//AFS_SEL=1 ±4 g
//AFS_SEL=2 ±8 g
//AFS_SEL=3 ±16 g

//
  accelgyro.setFullScaleAccelRange(0); //set range AFS_SEL to 0 currently.

//**************************************************************************

  // verify connection
  Serial.println("Testing device connections...");
  Serial.println(accelgyro.testConnection() ? "MPU6050 connection successful" : "MPU6050 connection failed");

  // configure Arduino LED for
  pinMode(LED_PIN, OUTPUT);

}
```

```
float angle = 0;
float vel_x = 0;
float disp_x = 0;
unsigned long dt =0;

void loop() {


  unsigned long start_time = millis();

  // put your main code here, to run repeatedly:
  accelgyro.getMotion6(&ax, &ay, &az, &gx, &gy, &gz);

  int gz_calibrated = gz - GZ_OFFSET;
  float gz_deg_sec = GYRO_SCALE*gz_calibrated;

  angle = angle + gz_deg_sec*dt/1000.0;


  float ax_g = ACCEL_SCALE*ax;
  float ay_g = ACCEL_SCALE*ay;
  float az_g = ACCEL_SCALE*az;

  vel_x = vel_x + ax_g*dt/1000.0;
  disp_x = disp_x + vel_x*dt/1000.0;
```

```
// display tab-separated accel/gyro x/y/z values
       Serial.println("a_g/g:\t");
       Serial.print(ax_g*100); Serial.print("\t");
       Serial.print(ay_g*100); Serial.print("\t");
       Serial.print(az_g*100); Serial.print("\t");
       //Serial.print(gx); Serial.print("\t");
       //Serial.print(gy); Serial.print("\t");
       //Serial.print(gz); Serial.print("\t");
       //Serial.println(angle);
       //Serial.println(disp_x);

   delay(50);
 // blink LED to indicate activity
   blinkState = !blinkState;
   digitalWrite(LED_PIN, blinkState);
   unsigned long end_time = millis();

   dt = end_time - start_time;
   //Serial.println(dt);
}
```