ASSESSMENT OF WHOLE BODY VIBRATION AMONG FORKLIFT DRIVERS USING ISO 2631-1 AND ISO 2631-5

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The following faculty members have examined the final copy of this thesis for form and content and recommended that it be accepted in partial fulfillment of requirements for the degree of Masters of Science, with a major of Industrial Engineering.

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DEDICATION

To my parents and my brother, who kept me continuously motivated with their great support and encouragement throughout my MS program and to my beloved Fiancée

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ABSTRACT

The use of forklifts to move material is very common in large manufacturing companies. Exposure to whole body vibration from industrial vehicles such as forklifts has been associated with low back pain and also with the degeneration of intervertebral disc. Predicted health risks, associated with the operation of forklifts, based on ISO 2631-1 criteria are limited and have not yet been determined according to ISO 2631-5 criteria. Therefore, the objective of this study was to quantify the whole body vibration exposure levels during the operation of different types of forklifts and to quantify WBV exposure levels using ISO 2631-1 and ISO 2631-5 standards. Hence, health risks predicted by ISO 2631-1 and 2631-5 criteria are reported and compared in this study. This research was conducted at a local aircraft manufacturing company in Wichita, KS. Vibration exposure was measured according to procedures established in ISO 2631-1. A tri-axial seat pad accelerometer was used to measure vibration exposure at the operator/seat interface. Vibrations were measured passively with the use of a battery-operated datalogger while employees drove their forklifts during a normal work day. The results were compared in accordance to frequency-weighted r.m.s values, vibration dose values, equivalent compressive stress S_{ed} and the R factor. According to ISO 2631-1 criteria, two forklift operators were identified to have a high risk of exposure and three forklift operators were identified to have a moderate risk of exposure in accordance with health guidance caution zone (HGCZ) boundaries with A (8) as a measure. Similar results were achieved from the S_{ed} and R factor values which were the measure of ISO 2631-5. Adverse health effects on the lumbar spine according to ISO 2631-5 were always lower than the risks predicted by ISO 2631-1 criteria. But, VDV (a measure of ISO 2631-1) showed similar results with ISO 2631-5 measures.

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CHAPTER 1

1.0 INTRODUCTION

Professional drivers are exposed to multiple factors which are considered risks for low back disorders. These factors include whole body vibration, constrained postures and repeated twisting or bending of the back and neck. For example, agriculture tractor drivers adopt risky postures, often a requirement to monitor a towed implement (Bovenzi and Betta, 1994). Construction and agricultural workers are also exposed to twisted postures for long periods (Magnusson and Pope, 1998). Occupational exposure to whole body vibration (WBV), particularly for heavy equipment operators, has increased over the past twenty to thirty years and a positive relationship between long term exposure to vibration and definite medical problems such as degeneration of intervertebral disc, and disc herniation have been shown (Seidel, 1993).

Predominantly, operators of mobile equipment, transport vehicles, heavy industrial vehicles, tractors, locomotives, buses and helicopters are exposed to unsafe levels of WBV (Bongers and Boshuizen, 1992). Schwarze et al. (1998) identified that occupational exposure to WBV instigating from operation of forklift trucks (forklifts) has been accredited as a significant risk factor for low back disorders (LBDs). The use of forklifts in the manufacturing, service and warehousing industries is accordingly prevalent with an estimated 1.2 million operators and as many as 800,000 forklifts in the United States alone (Schwarze et al., 1998). It is estimated that every year nearly 100 workers are killed and about 20,000 are seriously injured in forklift related incidents (National Institute for Occupational Safety and Health, 2001). It has also been estimated that there are about 90,000 forklift drivers working in occupational industries in the United Kingdom, whose working conditions may not be ideal (Palmer et al., 2003).

Waters et al. (2005) identified that the drivers of the forklifts have been shown to suffer musculoskeletal disorders due to various occupational risk factors. These factors include static sedentary position while driving (hands and feet held steady on handles and pedals); repeated exposure to short and long term awkward trunk posture (twisting and bending of trunk) particularly during reverse operation; and exposure to whole body vibration while driving. Waters et al. (2007) showed that in most cases WBV exposure involves two distinct components: 1) a continuous steady state component generated by the forklift power source and general operating characteristics (engine type, tires of forklift, type of seat etc.) and 2) a series of transient WBV shock events generated by travel over obstacles or uneven terrain. This transient mechanical shock is also commonly referred as 'jarring and jolting', which is a high acceleration event. Waters et al. (2007) indicated that there has been a very small amount of study on the effect of exposure to transient mechanical shocks.

ISO 2631-1 (1997) shows that exposure of whole body vibration is measured in three basicentric axes (x, y, and z axis) and is typically reported as frequency weighted r.m.s values. Vibration measurement, according to International Standards Organization (ISO) 2631-1 (1997), showed that vibration magnitude ranges from 0.79 to 1.04 m/s^2 in forklift trucks (Bovenzi & Hulshof, 1999). The dominant vibration transmitted through the seat of forklifts is often at frequencies between 4 to 12 Hz (Griffin, 1990). A handful of studies have attempted to differentiate between the effects of exposure to the two vibration components mentioned above. Jarring was reported as a cause of 36% of the back injuries to the mobile equipment operators (Cross and Walter 1994). Waters et al. (2007) identified that ISO 2631-1 (1997) accounts only for the steady state component generated by the forklift operation and does not account for the jarring and jolting components of vibration. In order to consider the jarring and jolting components of vibration, a new standard, ISO 2631-5 (2004), was developed, which also suggests boundaries for probable health effects on the lumbar spine.

There has been recent research on the outcome of ISO 2631-5 for vehicles such as load haul dump vehicles, mining vehicles and some army tracked-type vehicles. However, there has been no research on vibration quantification among the forklift vehicles according to ISO 2631-5. This indicates a necessity for research to be performed according to ISO 2631-5 for forklift vehicles. Although there are a few studies showing comparison between ISO 2631-1 and ISO 2631-5 with vibration quantification for load haul mining equipment vehicles and locomotives, there are no studies showing vibration quantification comparison for forklift vehicles.

Therefore, the first objective of this paper was to quantify the whole body vibration exposure levels during the operation of different types of forklifts. The second objective was to quantify WBV exposure levels using ISO 2631-1 and ISO 2631-5 and compare the health related outcomes in accordance to ISO 2631-1 and ISO 2631-5.

CHAPTER 2

2.0 LITERATURE REVIEW

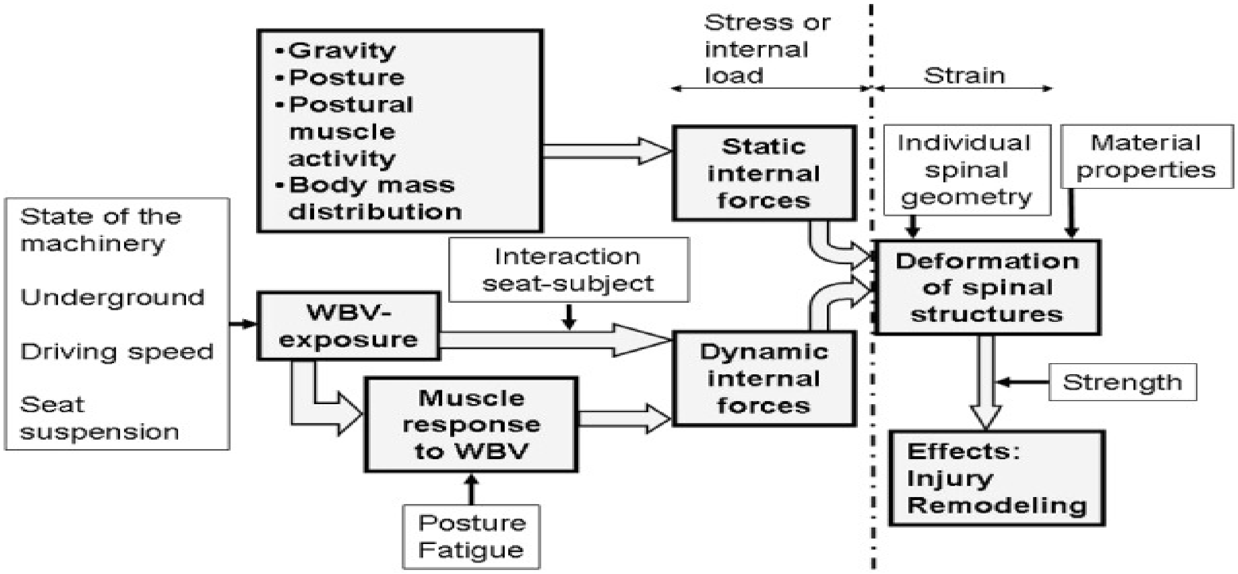
2.1 Whole Body Vibration

Whole body vibration (WBV) occurs when a body is supported on a vibrating surface, usually a seat or floor. WBV is an oscillation with frequency ranging from 0.01 to 50 Hz which is transmitted to the body that can cause motion sickness, discomfort, pain, vomiting, and paresthesia (numbness to the skin) (Uchikune, 2004). Vibration exposure to the human body is complex, since the human body is exposed to various frequencies in different directions (Griffin, 1990).

Due to the whole body vibration, the body is exposed to physiological and pathological effects (Griffin et al., 1990). Whole body vibration exposure can produce a vascular change (which enables the passage of respiratory gases, nutrients, excretory products, and other metabolites into and out of the cells) that results in nutritional compromise of the tissues around the spine. These vascular changes results in muscle fatigue and compression of the discs (Magnusson et al., 1998). When sitting occurs in a vibration environment, it can lead to an additional rocking of the pelvis rotation which may amplify the vibration transmitted to the spine, and may also increase the rate of disc degeneration (height of the spinal disc reduces gradually) (Wilder, 1993).

Seidel (1993) indicated that WBV-exposure is defined as the vibration measured at the interfaces between the machine and the operator, i. e. mainly at the driver seat. The spinal health risk arises from a mechanical damage of anatomical structures due to forces (internal load) acting on these anatomical structures. The internal forces do not depend solely on the WBV-exposure. Therefore, the assessment of the spinal health risk of WBV-exposure may not be restricted to a straightforward relationship between WBV-exposure and low back pain. A clear conceptual framework is shown in figure 2.1, which can help to clarify the factors determining the effects of WBV on spinal health and contributing to the internal stress-strain relationship during WBV-exposure.

Figure 2.1: Conceptual framework of the relationship between WBV vibration exposure and spinal health (Seidel, 1993).



Seidel (1993) showed from figure 2.1 that WBV-exposure itself depends upon several factors like the driving speed, seat suspension and type of vehicle. The WBV-exposure causes an acceleration of the human body with related dynamic forces acting on the spine. Further dynamic internal forces arise from the muscle response with alternating increased and decreased activity of the low back muscles. Low back muscles can either exert very high forces on the spine or cause spinal instability by relaxation. Their response to WBV also depends on the posture and muscle fatigue. Gravity causes the static portion of internal forces with posture, postural muscle activity and body mass distribution as significant variables. Extended (leaning backwards) and flexed (leaning forward) prolonged seated torso postures can have significantly different effects on the force components in the lumbar spine. Static and dynamic internal forces add up to the stress (internal load) that causes the strain (deformation) of spinal structures. The outcome of the strain depends on the strength of spinal structures and their ability to recover from repetitive load. Negative health outcomes due to whole body vibration can include low back pain, spinal degeneration, sleep problems, headaches, and neck problems (Seidel, 1993).

Bongers and Boshuizen (1992) hypothesized that exposure to WBV causes direct structural damage of: 1) the end plate of the vertebral body 2) the annulus fibrous of the intervertebral disc, and 3) the facet joints of the spine. From figure 2.2, exposure to whole body vibration leads to dynamic loading on the spine which directly affects the endplate and the subchondral bone, annulus fibrosis, and facet joints of the lumbar spine. The nutrition of the intervertebral disc is indirectly (microfractures of the endplate induce callus formation) affected due to exposure to WBV, ultimately reducing the height of the intervertebral disc. In order to resist the dynamic loading due to exposure to WBV the response of the muscles of the back are increased which may lead to muscle fatigue of the lower back (Bongers and Boshuizen, 1992).

When vibration occurs at a frequency which is equal to the natural frequency (the unforced vibration of the body), a resonance (vibration occurring at maximum magnitude) occurs, which leads to large internal stresses and strain (Wilder and Pope, 1996). The epidemiological evidence showed that there is a strong association between forklift operation and lower back pain; this association is consistent among studies evaluated (Viruet et al., 2008). The possible main factors that expose forklift operators to the risk of developing lower back pain were WBV and awkward torso postures (Viruet et al., 2008).

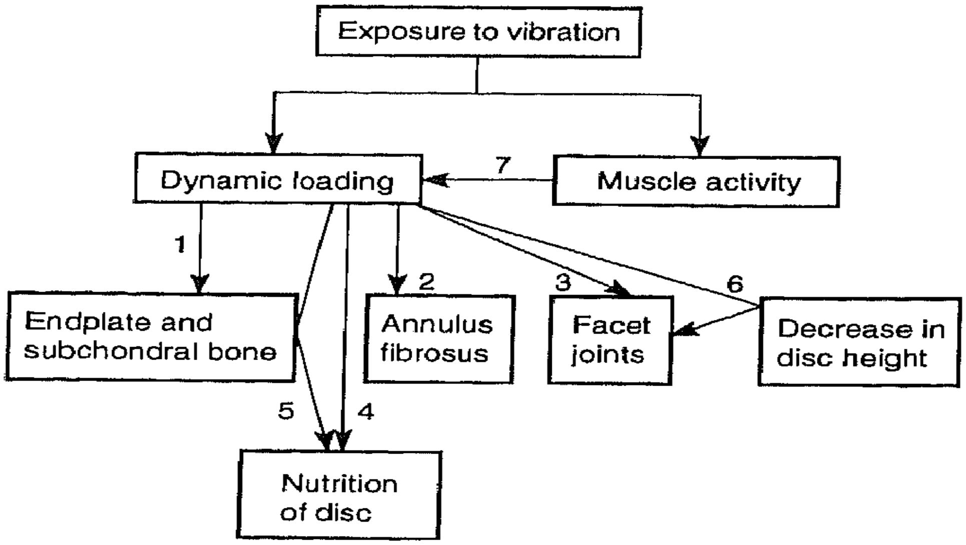


Figure 2.2: Hypothesis on the mechanisms of exposure to vibration and structural spinal damage (Bongers and Boshuizen, 1992).

Bovenzi and Hulshof (1998) aimed their paper to update the epidemiological evidence of adverse health effects of WBV as risk factor for low back pain. A cross sectional study was performed among the forklift drivers as a study group for a period of twelve months. The results showed that the odds ratio among the forklift drivers for low back pain was 7.3 (95% CI 2.5 to 22), indicating that the operators who are exposed to WBV are at significantly increased risk of developing low back pain.

Viruet et al. (2008) indicated that according to ISO 2631 – 1 (1997) the magnitude of frequency-weighted r.m.s acceleration among forklift operators can range from 0.8 to 1.04 m/s^2 for vertical z-direction which may exceed the caution zone values in comparison to ISO 2631-1. This could result in an adverse health effect on the lumbar spine. The acceptable 8 and 12–hour average vibration exposure levels in the vertical z-direction for ISO 2631–1 are shown in Table 2.1 (Viruet et al., 2008).

Table 2.1: Permissible 8 – hour and 12 – hour average vibration exposure, ISO 2631-1 (1997).

Exposure Duration	Likely health risk	Caution Zone	Comfort level
8 - hours	0.8 m/s^2	0.5 m/s^2	0.315 m/s^2
12 - hours	0.7 m/s^2	0.4 m/s^2	0.315 m/s^2

According to several studies (Viruet et al. 2008; Bovenzi and Hulshof, 1998; Wilder et al., 1996; Bongers and Boshuizen, 1992; Water et al. 2007 etc.) there is sufficient evidence of a relationship between exposure to WBV and low back pain. Exposure to WBV has shown an adverse health effect on the lumbar spine, such as low back pain and/or low back disorders or degeneration of the intervertebral disc. The range of exposure of WBV vibration ranges from 0.2 to 1.8 m/s^2 for vehicles like forklifts, which can essentially be compared with the health guidance caution zone (HGCZ) in ISO 2631-1, in order to identify the safe limits of the WBV exposure.

2.2 Transportation Equipment – Forklifts

Forklifts can be classified depending upon various characteristics. Viruet et al., (2008) classified types of forklift upon the description shown in Table 2.2.

Table 2.2: Types of forklifts (Viruet et al., 2008).

Type of forklift	**Description**
Class I forklift	Rider trucks, either stand-up operator or seated three-wheel units, with an electric motor. They usually are counterbalanced with cushion or pneumatic wheels.
Class II forklift	Electric motor vehicles used in narrow aisle or inventory stock picking functions and may include extra reach or swing mast options.
Class III forklift	Vehicles with a walk-behind or standing rider controller and have electric motors. They are commonly automated pallet lift trucks and high lift models, and are usually offset.
Class IV forklift	Vehicles with cabs and seated controls for a rider, and they have internal combustion engines.
Class V forklift	Rider fork vehicles that feature cabs and seated controls and have internal combustion engines.
Manual drive forklifts	Manually move the load and are controlled by a person walking behind the lift.
Motorized drive forklifts	Include a cab or seat for the driver to operate the vehicle while riding in it.
Narrow aisle trucks	Vehicles that can operate in aisles typically 8 to 10 feet clear.
Pallet trucks	Common and outfitted for specific use with pallets in storage, warehouse and manufacturing settings.
Platform trucks	Have a load platform intended to pick up and deposit a customer’s specific type of skid.
Side loads	Equipped to reach forward to pick up or deposit long, heavy loads or pallets and are able to work in very narrow aisles.

Forklifts can also be classified based on several features such as the manufacturer of the forklift, the model of the forklift, the load carrying capacity (ranging from 1 to 10 ton), the type of engine (diesel, electric and propane gas), the type of tires (solid and pneumatic), and seat adjustments.

Waters et al. (2005) indicated a new framework, which considers both steady state and transient mechanical shock components of vibration and assess low back pain due to mechanical multiple shocks, is needed. There is a need to fully understand the vibration exposure such as mechanical jerk (non–cyclic forces) or the transient component of WBV induced by traveling over obstacles or uneven terrain. However, few studies have attempted to discriminate between the sinusoidal vibrations or the steady state (cyclic forces acting over a range of frequencies) and transient mechanical shocks or shock loads (non–cyclic forces acting for a very short period of time). As a result, it is difficult to draw any conclusions about the relative impact of the two types of vibration exposure on the development of LBDs due to the lack of quantitative data (Waters et al., 2007).

Some aspects of the work environment that influence vibration exposure (steady state vibration) are seat, speed, track and tires. As there are different types of tires, seats, and models of forklifts available with different specifications, the vibration transmission is affected (might be elevated or may be reduced) depending upon the characteristics of the factor (Viruet et al., 2008). Malchaire et al. (1996) showed that forklifts are fairly common in several aircraft and auto manufacturing industries where the main cause of low back pain among the forklift drivers was exposure to WBV. In addition, technical characteristics of the forklifts such as soft cushion tires in front and rear, hard cushion tires in the front and the rear, and inflated tires in the front and in the rear have different effects on transmission of a steady state vibration as well as on the mechanical shock vibration. The result showed that the inflated cushion tires were a better option to reduce the magnitude of vibration. When frequency-weighted r.m.s values were compared for a rough surface with a concrete smooth surface the frequency-weighted r.m.s values were higher for the rough surface. The amount of load carried by the forklift also has an effect in reducing the magnitude of vibration. The heavier the load carried by the forklift the lower the magnitude of the acceleration transmitted. The forklifts driven by an electric power source have less vibration with significant reduction of 0.2 m/s^2 in acceleration for z-direction when compared with a diesel engine forklift.

Malchaire et al. (1996) quantified WBV, for forklifts with two different types of seats: 1) a seat without an anti-vibration system, and 2) a seat with a mechanical anti-vibration suspension, while driving on a rough paved track and a smooth concrete track. The frequency-weighted equivalent accelerations for the z-direction were always lower for the seat with the anti-vibration system and for the smooth concrete track. The frequency-weighted r.m.s accelerations for a seat without the anti-vibration system and for a seat with the anti-vibration system were observed to be 1.90 m/s^2 and 1.29 m/s^2 respectively. The frequency-weighted r.m.s accelerations for a rough paved track and for a concrete smooth track were observed to be 2.01 m/s^2 and 1.18 m/s^2 respectively. Therefore, if a forklift is provided with a seat with an anti-vibration system and driven on a smooth track of concrete the vibration exposure levels may be reduced.

Sandover (1988) indicated that epidemiologic studies have shown long term health problems particularly due to shock vibration which leads to musculoskeletal disorders of the low back. Epidemiological studies investigating the long term effects of WBV have primarily considered the health of the spinal system and, to a lesser degree, the gastrointestinal (ingestion, digestion, absorption, and defecation) system (Bovenzi, 1996). Wilder and Pope (1996) showed that the prevailing vibration transmitted through the seat of the forklift trucks is often at frequencies between 4 to 12 Hz. Typical WBV exposures levels of heavy-vehicle drivers are in the range of 0.4 to 2.0 m/s^2 with a mean value of 0.7 m/s^2 in the vertical axis. The resonance of the human spinal system occurs most often within the band 4.5–5.5 Hz. If vibration occurs at a frequency that is identical to the natural frequency period of body tissue, resonance may occur, which could lead to large internal stress and strain.

Hoy et al. (2005) assessed the whole body vibration and postural load among forklift operators in which low back pain was the outcome. A cross–sectional study was carried out which included 23 forklift operators and 23 workers from the other departments who did not drive vehicles at work (control group) at a paper mill company in the United Kingdom. Whole body vibration measurements in three orthogonal axes were carried out for twelve actual working conditions (movement over and across the different ground surfaces and during performance of different tasks–stacking loads, picking up and loading trucks). The measurements were done according to the recommendations of ISO 2631-1. From video recordings, bending, leaning and twisting postures were identified as the frequent postures adopted by the forklift operators. The paper concluded that LBP was more prevalent among the forklift drivers than non–driving workers. The magnitude of acceleration in the x-axis (for-aft) and y-axis (lateral) were found to be much lower than compared to the vertical z-axis. Odds ratio for low back pain to forklift operators when exposed to WBV, was observed as 3.52 (95 % CI 1.04–11.83). The mean acceleration for the z-axis was found to be 0.57 m/s^2 while that in x-axis and y-axis was found to be 0.31 m/s^2 and 0.29 m/s^2, respectively (Hoy et al., 2005).

Boshuizen et al. (1990) showed a strong association between forklift operators and lower back pain. From an epidemiological point of view the possible factors that expose forklift operators to the risk of developing low back pain are whole body vibration and non–neutral (awkward postures adopted by the drivers) driving postures.

Due to work requirements, hazardous postures are often adopted by the forklift drivers. For example, forklift drivers often twist to look behind for safety checks while reversing (Paddan and Griffin, 2002). Eger et al. (2006) identified that many individuals adopt twisting of the trunk, flexion of the trunk for more than 25% of their work cycle, in addition to neck twisting for more than 22% of their work cycle. The operators were also exposed to relatively high magnitudes of whole body vibration and operating manual controls. One particular operator had his neck twisted greater than 40 degrees for 93% of a 60 minute work cycle.

Viruet et al. (2008) discussed an evidence-based approach to find the relationship between whole-body vibration and driver postures with lower back pain among forklift operators, and to develop recommendations to minimize risk factors for low back pain. The essential steps for the approach were: 1) formulation of a clear research question from a worker occupational problem, 2) critically appraise the evidence, 3) search of the literature for the best evidence with which to answer the question, and 4) implement useful findings in occupational health and safety practices. A meta-analysis was carried out to estimate an overall odds ratio on lower back pain among heavy equipment operators (meta-odds ratio). The meta relative risk was 2.1, indicating that the operators exposed to driving forklifts are at a greater risk of getting lower back pain to those not exposed to driving forklifts. Some of the health hazards among operators of heavy equipment are whole body vibration (WBV; steady state and/or transient) and awkward postures (including static sitting, trunk twisting and bending, neck flexion and rotation).

Newell and Mansfield (2008) investigated the effect of armrests of the forklifts on the reaction time and perceived workload of the subjects exposed to whole body vibration. The experimental design consisted of running tests with providing armrests and without armrests. The seat was simulated by transmitting vibration of magnitude 1.1 m/s^2 in vertical z-direction and 1.4 m/s ^{2} in the x-direction. It was concluded that during vibration exposure, the absence of arm support greatly reduced the participant's ability to drive the forklift.

Shinozaki et al. (2001), in an intervention study for prevention of low back pain in Japanese forklift workers, identified two approaches: 1) a personal approach which consisted of providing lumbar support on the seat of a forklift and physical exercise; and 2) a facility approach which included the improvement of forklift seats (suspended seats) and tires (pneumatic). Suspended seats and pneumatic tires were used as an intervention instead of fixed seats and punctureless tires, respectively. The self-reported prevalence of LBP was surveyed three times before and after the two interventions from 260 male blue-collar workers including 27 forklift workers, and 55 male white-collar workers of a copper smelter. The initial prevalence of LBP was 63% in the forklift workers, which was significantly higher than that found in the other blue-collar workers (32%) and in the white-collar workers (22%). One year after the first intervention (personal approach) to the forklift workers, the prevalence of LBP fell to 56%. The second intervention (facility approach), which was mainly comprised of suspended seats and pneumatic tires on the forklift truck, reduced whole body vibration, and nine months later the prevalence of LBP in the forklift workers further decreased to 33%. The reduction of the prevalence from the initial survey was significant (p=0.008), and that from the second survey was nearly significant (p=0.070). These findings suggest that the facility (changing the tires and seats) approach may be more effective for a reduction of LBP than the personal approach (lumbar support to the seat and physical exercise).

At this point there appears to be a relationship between exposure to WBV and low back pain. Also, the evidence of occurrence of LBP from the exposure to WBV among the forklift drivers has been shown from some of the authors mentioned above such as Viruet et al. (2008), Boshuizen et al. (1990), and Hoy et al. (2005). Furthermore, WBV is comprised of two components: 1) a continuous steady state vibration and 2) a series of transient WBV mechanical shock also called as jarring and jolting. Studies by Waters et al. (2007) have shown that assessment of whole body vibration is performed in accordance to ISO 2631-1 (1997) which accounts for the first component of WBV i.e. a steady state vibration and likely does not account for the mechanical shocks. Hence, a new standard ISO 2631-5 (2004) was developed to account for the mechanical shocks or to consider the jarring and jolting occurrence during operation of forklifts. Therefore, quantification of WBV among the forklift drivers is necessary in accordance with the new standard, ISO 2631-5 (2004).

2.3 Quantifying Vibration Exposure

The primary purpose of ISO 2631 – 1 (1997) is to define methods for quantifying whole body vibration in relation to a) human health and comfort, b) the probability of vibration perception and c) the incidence of motion sickness. ISO 2631-1 excludes hazardous effects of vibration transmitted directly to the limbs (e.g. by power tools). ISO 2631-1 defines methods for the measurement of periodic, random and transient whole body vibration. It also determines the degree to which vibration exposure may be acceptable.

Vibration which is measured by an accelerometer should be measured according to the coordinate system shown in figure 2.3. Vibration should be measured on the surface between the body and the seat interface by placing the accelerometer on the seat pad. The vibration evaluation, according to ISO 2631-1, includes measurements of the frequency-weighted root-mean-square (r.m.s) acceleration, expressed in m/s^2.

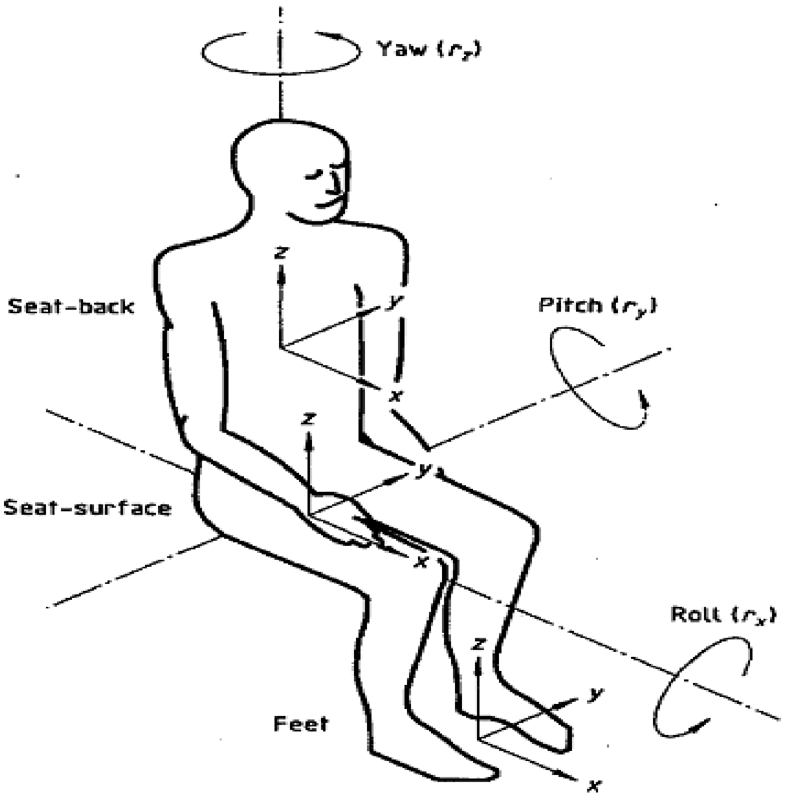


Figure 2.3: Basicentric axes of the human body.

The frequency-weighted r.m.s acceleration can be calculated using equation (1) in frequency domain for x-axis, y-axis and z-axis: equation (1) is referred from ISO 2631-1 (1997)

$$a_w=[1/T \int a_w^2(t)dt]^{1/2} \qquad (1)$$

where,

a_w = frequency-weighted acceleration in the x-axis, y-axis and z-axis

T = duration of measurement

Eger et al. (2006) measured whole body vibration exposure levels during the operation of fifteen different types of mobile mining equipment commonly used in Ontario mines. A tri-axial accelerometer, which was secured on the floor of the load haul dump cab between the operator's feet, was used to measure vibration exposure when the mining equipment was operated from a standing position. Measurements were conducted in accordance with the procedures described in the 1997 ISO 2631-1 standard. Six vehicles (haulage truck, bulldozer, 3.5 yard LHD, cavo loader, muck machine, and personnel carrying tractor) were above the Health Guidance Caution Zone limit (0.9 m/s^2), assuming an eight hour exposure period for the dominant vertical z-axis. Four vehicles (grader, 7 yard LHD, scissor lift truck and locomotive) were within the Health Guidance Caution Zone limit (0.45 m/s^2 – 0.9 m/s^2).

Cann et al. (2004) aimed their study at WBV exposure levels experienced by transport truck operators in order to determine whether operator's exposure exceeded the 1997 International Standards Organization (ISO) 2631-1 WBV guidelines. The variables selected were based on previous literature and the author's transportation specialist group, and included road condition, truck type, driver experience, truck mileage, and seat type. Tests were conducted on four major highways with five minute random samples taken every thirty minutes of travel at speeds greater than or equal to eighty km/hr (i.e. highway driving). Results showed that operators were not on average at increased risk of adverse health effects from daily exposures when compared to the ISO 2631-1 WBV guidelines. Regression models presenting the frequency-weighted r.m.s acceleration values for the x-axis ($F_{(5,97)}=8.63$, $p<0.01$), y-axis ($F_{(5,97)}=7.74$, $p<0.01$), z-axis (F(5,61)=9.83, $p<0.01$) axes and the vector sum of the orthogonal axes ($F_{(5,61)}=13.89$, $p<0.01$) were developed. According to the author's transportation specialist group, the rough road (rough surface, potholes, narrow road and limited shoulder condition)

condition was a significant predictor ($p<0.01$) when compared to smooth road, for the frequency-weighted r.m.s accelerations for all three axes and the vector sum of the axes. In addition, two truck types: 1) cab-over (cabinet assembled above the seats) and 2) cab-behind (cabinet assembled behind the seats) were compared to identify the significant truck type for r.m.s accelerations. Cab-over trucks were observed to have an elevated ($p<0.01$) frequency-weighted r.m.s accelerations when compared with cab-behind trucks for the z-axis and vector sum. Future research should explore the effects of seasonal driving, larger vehicle age differences, greater variety of seating and suspension systems and team driving situations.

Eger et al., (2008) showed a comparison of predicted health risks based on ISO 2631-1 and ISO 2631-5, and provided data that could suggest the ISO 2631-5 boundaries for probable health effects may be set too high (under-protective). Their study was based on predictions of health risks associated with the operation of load-haul-dump mining vehicles. A tri-axial seat pad accelerometer was used to measure vibration exposure at the operator/seat interface. According to ISO 2631-1 criteria, calculated 8-h equivalent vibration dose values (VDV's) placed three of the seven LHD operators above the health guidance caution zone (HGCZ) boundaries and four LHD operators within the HGCZ. However, the results showed that the health risks predicted by the ISO 2631-5 criteria were always lower than the risks predicted by ISO 2631-1 criteria.

According to ISO 2631-5, an R factor is determined for the assessment of the adverse health effects related to the human muscle response (muscles of the low back or lumbar region). R values below 0.8 indicate a low probability of adverse health effects to the lumbar spine while values greater than 1.2 suggest a high probability of adverse effects. Similarly, a daily equivalent static compression dose (S_{ed}) is also determined for the assessment of the adverse health effects related to the human response (muscles of the low back or lumbar region). S_{ed} values below 0.5

MPa reflect a low probability of an adverse health effect to the lumbar spine while values greater than 0.8 MPa suggest a high probability of adverse health effects. Equations (2) to (5) are referred from ISO 2631-5 (2004).

Equation (2) is used to determine the acceleration dose, D_k, in m/s^2

$$D_{k} = [\Sigma A_{ik}{}^{6}]^{1/6} \tag{2}$$

where,

A_{ik} = ith peak of the response acceleration, where the peak is defined as the maximum absolute value of the response acceleration between two consecutive zero crossings;

$D_{kd} = D_k\,[t_d/t_m]^{1/6}$; is the average daily dose in m/s^2; (3)

t_d = duration of the daily exposure;

t_m = period over which D_k has been measured.

The daily equivalent static compression dose, S_{ed} is calculated according to equation (4), where m_k are constants for the x, y and z directions (0.015, 0.035 and 0.032 MPa, respectively). Recommended values from ISO 2631-5 for the constants are m_x = 0.015 MPa, m_y = 0.035 MPa, m_z = 0.032 MPa, and D_{kd} is the average daily dose:

$$S_{ed} = [\sum (m_k D_{kd})]^{1/6} \text{ MPa} \tag{4}$$

Factor R is calculated according to equation (5) where, i represents the year the vibration exposure starts, n is the number of years exposure, c is a constant representing the static stress due to gravitational force, S_{ui} is the ultimate strength of the lumbar spine for a person of age (b + i) years, and b is the age that the vibration exposure started;

$$R = [\sum (S_{ed}{}^{1/6} / S_{ui} - c)^{6}]^{1/6} \qquad (5)$$

Alem (2005) indicated that the U.S Army Aeromedical Research Laboratory conducted research to extend a method for health hazard assessment of strategic ground vehicles. This paper described the health prediction by comparing the new multiple shocks standard ISO 2631-5 with the earlier whole body vibration standard ISO 2631-1. Alem (2005) also described a software tool which was developed to implement both parts of ISO 2631. Tracked-type and wheeled vehicles were used in this study. The results were compared based on vibration dose values (VDV) reported in $m/s^{1.75}$, S_{ed}, and the R factor. According to ISO 2631-1, a VDV value below 8.5 $m/s^{1.75}$ indicates low adverse health effects on the lumbar spine, VDV values between 8.5 – 17 $m/s^{1.75}$ indicates moderate adverse health effects on the lumbar spine and VDV value above 17 $m/s^{1.75}$ indicates high adverse health effects on the lumbar spine. The comparison showed that the new standard (ISO 2631-5) was more sensitive (estimated higher health risk effects to the lumbar spine than ISO 2631-1) to the cross-country terrain compared to the Belgian block terrain, washboard terrain and paved roads than the current ISO 2631-1.

Cooperrider and Gordon (2008) measured shock and impacts on locomotives and evaluated WBV with the vibration dose value (VDV) (a measure of ISO 2631-1) and with the spinal stress S_{ed} method (a measure of ISO 2631-5). The vibration data were collected for more than 90 hours, and from different locomotive models at different locations within United States of America. According to analysis the results resulted that shocks and impact showed a low probability of adverse health effects on the lumbar spine. The highest VDV value exceeded the lower HGCZ boundary of 8.5 $m/s^{1.75}$, while the S_{ed} value were always below the boundary for low probability of adverse health effect on lumbar spine. VDV was found to be more stringent for evaluating shock and impacts for locomotives when compared with the spinal stress S_{ed}

method. Therefore, when ISO 2631-1 and ISO 2631-5 measures were compared for adverse health effects on the lumbar spine, ISO 2631-5 (S_{ed} measure) resulted in lower risks compared to that predicted by ISO 2631-1 criteria.

Johanning et al. (2006) carried out a quantification of WBV for railroad locomotives for fifty different locomotives. The data were analyzed using both the ISO 2631-1 and ISO 2631-5 measures. The results of the vibration and shock measurement for the basic A (8) were found to be in a range of 0.27 to 0.65 m/s^2 for vertical z-axis indicating that the values exceed the HGCZ given by ISO 2631-1. Similarly, for some subjects VDV values exceeded the HGCZ values given by ISO 2631-1. The daily equivalent static compression dose S_{ed}, a measure of ISO 2631-5 was observed with a mean value of 0.32 MPa, indicating a low probability of adverse health effect on lumbar spine. Similarly, the R factor which is also a measure of ISO 2631-5 showed possible disagreement with ISO 2631-1 results, as the mean value was observed to be 0.34, indicating a lower adverse health effects on the lumbar spine. Hence the new standard ISO 2631-5 for evaluation of vibration containing multiple shocks suggests a low probability of exposure risk on lumbar spine from the current results. Therefore, the authors proposed to consider a combined sum score, in an overall risk assessment, which included ergonomic co-factors such as awkward body postures and cab and seat design.

In summary, Eger et al. (2008) identified that the ISO 2631-5 measures predicted lower probability of adverse health effect on the lumbar spine for load haul dump trucks when compared to ISO 2631-1 measures. In contrast, (Alem 2005) indicated that the ISO 2631-5 measures predicted a higher risk of exposure to the lumbar spine in a study of U.S. Army vehicles. Cooperrider and Gordon (2008) from their shock and impact level study on locomotives showed that the ISO 2631-1 measure, particularly VDV is more stringent (showed high risk of adverse health effect on the lumbar spine) when compared to the daily equivalent static compression dose S_{ed}, a measure of ISO 2631-5. According to Johanning et al. (2006) ISO 2631-5 measures predicted low probability of adverse health effect on the lumbar spine for railroad locomotives when compared to ISO 2631-1 measures.

2.4 Research Void and Research Objectives

It is clear that a positive association between whole body vibration and low back pain has been demonstrated. Previous studies have carried out whole body vibration assessment among the forklift drivers in accordance to ISO 2631-1, which suggests it may not be protective enough for vibration exposure containing multiple shocks. These limitations were to be addressed in ISO 2631-5. However, to date there has been no published data of the quantification of WBV among the forklift drivers in accordance to ISO 2631-5. Additionally, there has been a little comparison of the health related outcome in accordance to ISO 2631-1 and ISO 2631-5, specifically for the forklifts.

Given the above research voids, the objectives of this research were two-fold. The first objective was to quantify the whole body vibration exposure levels during the operation of different types of forklifts. The second objective was to quantify the vibration exposure using ISO 2631–1 and ISO 2631–5 standards and assessment of predicted health effects on the lumbar spine and compare the health related outcomes in accordance to ISO 2631-1 and ISO 2631-5.

CHAPTER 3

3.0 METHODS

3.1 Approach

This study was performed at a local aircraft manufacturing company in Wichita, KS. A seat pad (thin rubber pad), which houses a tri-axial accelerometer to measure the vibration, was taped to the seat of the forklift truck. Vibration data were collected during the normal operation of the forklift, which lasted between two and four hours. A body part discomfort survey was carried out at two different timings (before recording and at the end of recording). Using this arrangement the vibration data were collected and analyzed using the Vibration Analysis Toolset software. A comparison of predicted health risks, based on ISO 2631-1 and ISO 2631-5, was then performed.

3.2 Subjects

Seven full-time forklift drivers were recruited as subjects for this study. The forklift drivers were identified by management of the company, upon which the WSU researchers approached the subjects and discussed their willingness to participate. Each subject was given a consent form (approved by the WSU Institutional Review Board (IRB) for Human Subjects – see Appendix A). After signing the consent form a demographic questionnaire and a body part discomfort survey of the participants were completed. Table 3.1 shows the summary of demographic details of the participants.

Table 3.1: Summary of demographic details of the participants

Variables	Mean	Standard Deviation (SD)
Age (Years)	48.4	4.2
Weight (Kg)	83.4	4.4
Height (cm)	178.0	3.3
Years of Exposure to WBV	12.5	4.2
Body Mass Index (BMI)	28.0	3.5

3.3 Experimental Equipment

A tri-axial accelerometer connected to a battery-operated datalogger was used to collect the whole body vibration data in the three basicentric axes (x–horizontal, y–lateral and z-vertical). The accelerometer was mounted in a thin rubber seat pad, and the seat pad was then taped to the seat of the forklift. Figure 3.1 shows the accelerometer and the datalogger. The whole body vibration data were collected during the normal operation of the forklift.

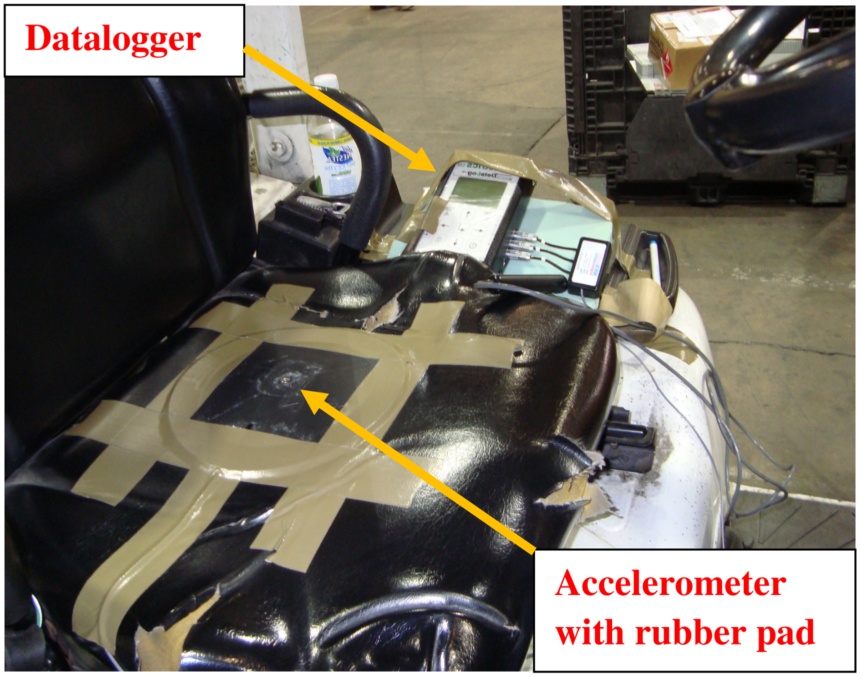


Figure 3.1: Accelerometer mounted in a seat pad taped on the forklift seat, and a Datalogger.

3.3.1 Accelerometer

A tri-axial accelerometer (Biometrics, Model S2-10G-MF, NexGen Ergonomics, Montreal, Quebec, Canada) shown in figure 3.2, and a battery–operated datalogger (Biometrics, P3X8, UK) were used. The three silver four-pin plugs of the S2-10G-MF accelerometer were connected to three analog channels of the datalogger. Table 3.2 shows the channel configuration of the accelerometer with the datalogger.

Table 3.2: Configuration of Accelerometer with DataLOG.

Data LOG analog channel	**S2-10G-MF accelerometer axis**
1	X
2	Y
3	Z

Figure 3.2: S2-10G-MF accelerometer.

The accelerometer receives all the power required for operation through the X, Y, and Z channel plug. Three channels for x, y and z –axis, in the datalogger, were configured as shown in Table 3.3. The acceleration in the three basicentric axes was recorded in G with a sampling rate of 500 Hz for each channel.

Table 3.3: Channel configuration using Biometrics Datalogger software.

Channel title	Accel X, Accel Y, Accel Z
Channel sensitivity	1V
Sampling rate	500 Hz
Excitation output	4500 mV
Zero	0
Full Scale	10
Units	G

3.3.2 Data LOG

The battery operated datalogger collected the vibration passively. Thus there was no subject involvement regarding the operation of the accelerometer or datalogger. Figure 3.3 shows a battery operated DataLOG.

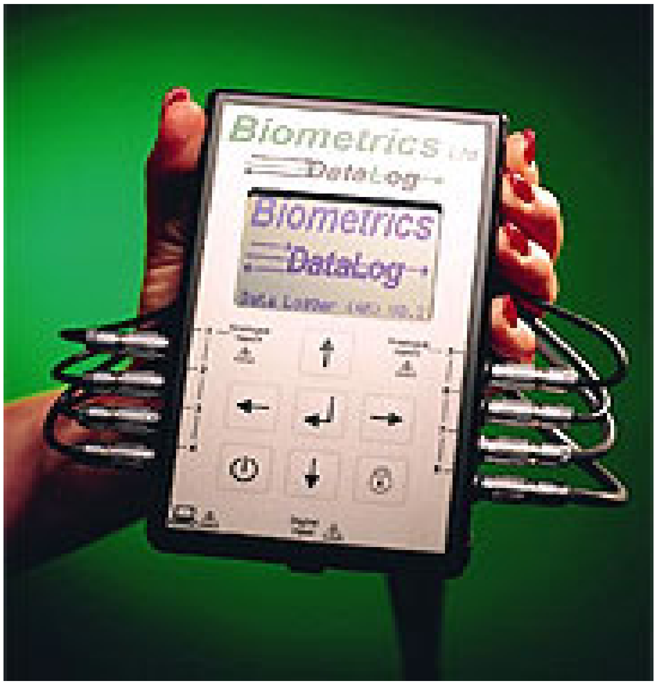


Figure 3.3: Biometrics DataLOG.

3.3.3 Time Marker

A time marker was used while recording the vibration data. The purpose of this time marker was to make a distinction between the peaks/spikes of vibration that appeared during the regular operation of forklift and peaks/spikes of voltage that occurred when getting off or on the seat. The rationale of differentiating these spikes is that, peak/spikes occurring while sitting on the seat of the forklift is not actual vibration data, but it is just a high voltage spike, that occurred from sitting on the seat. Thus, the time marker spikes indicate transitions between operation of the forklift, and getting up or sitting down on the seat while the forklift was not in operation. This allowed identification of vibration data due to actual operation of the forklift to only be used for analysis of whole body vibration. Figure 3.4 shows the time marker attached to a datalogger.

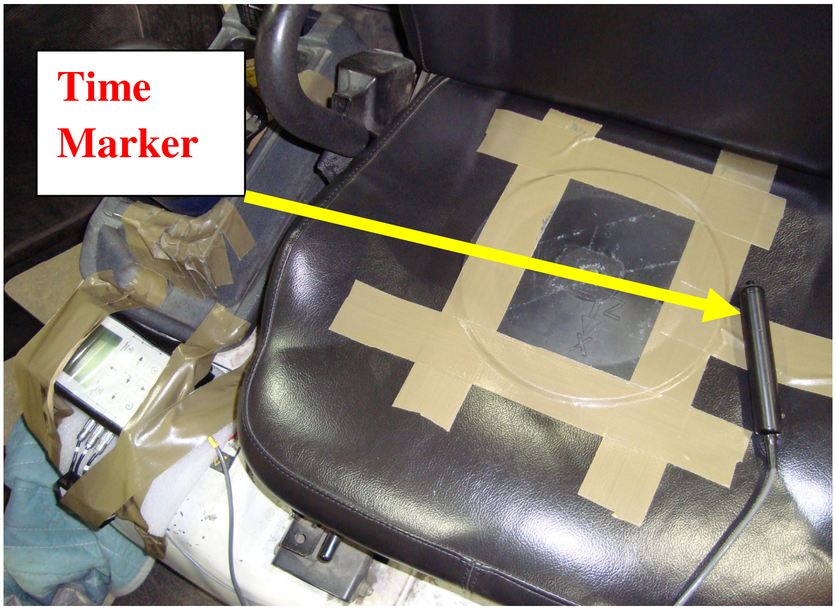


Figure 3.4: Time marker attached to the datalogger.

3.4 Experimental procedure

All the participants for this study were briefed about the study before signing the consent form. Demographic data such as gender, age, years of experience driving a forklift, height, weight, and smoking status, were collected prior to vibration recordings. The datalogger and the thin rubber pad were securely taped in the cab of the forklift. The vibration data were collected during the routine operation of the forklift. Figure 3.5 shows the experimental set up with an accelerometer mounted with a seat pad.

Figure 3.5: Experimental set up with an accelerometer mounted with a seat pad.

A body part discomfort survey (Figure 3.6) was completed before and after the collection of the vibration data. This body part discomfort survey was carried out in order to ascertain the location and magnitude of any perceived musculoskeletal discomfort at that point in time. Technical specifications of the forklifts used for collecting the vibration data were recorded, which included: 1) load capacity of the forklift, 2) type of tires used on the forklifts, 3) engine used in the forklift, 4) manufacturer of the forklift, and 5) seat adjustments/cushioning of the seats. After the vibration data were collected a low back pain questionnaire was conducted, inquiring about the location, frequency duration and severity of any low back pain experienced (Dionne et al 2008). This low back pain questionnaire is shown in figure 3.7. The low back pain questionnaire also asks about the smoking status of the forklift operator.

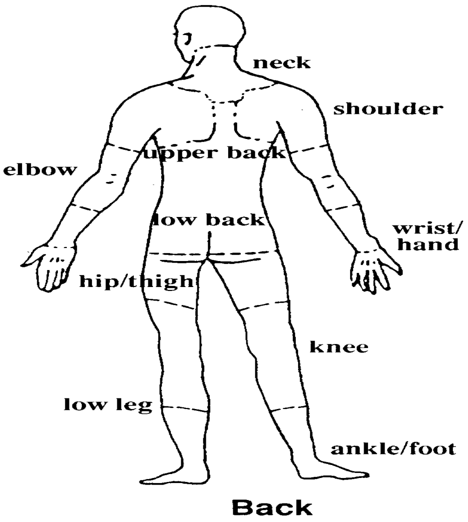
The vibration data collected by the datalogger was downloaded and analyzed using software, Vibration Analysis Toolset (NexGen Ergonomics, Montreal, Quebec, Canada) at the WSU Human Performance and Design Lab, 02A Wallace Hall. Similarly, the data from the body part discomfort was coded and analyzed on computers, also in the Human Performance and Design Lab.

Subject ID: ____________________ **Date:** _____________

DISCOMFORT SURVEY

No Pain Worst pain

0------1------2------3------4------5------6------7------8------9------10



Time: _______ Time: ________

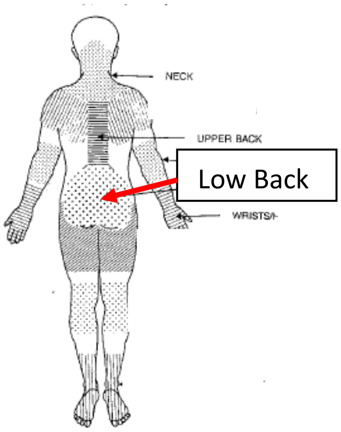
Discomfort Area	Rating Score	
	Right	Left
Neck		
Shoulder		
Elbow/Forearm		
Hand/Wrist		
Upper Back		
Low Back		
Hip/Thigh		
Knee		
Lower Leg		
Ankle/Foot		
Other:		

Discomfort Area	Rating Score	
	Right	Left
Neck		
Shoulder		
Elbow/Forearm		
Hand/Wrist		
Upper Back		
Low Back		
Hip/Thigh		
Knee		
Lower Leg		
Ankle/Foot		
Other:		

Figure 3.6: Body part discomfort survey.

Low back pain questionnaire for participation in the study

1) Subject ID : ______________________________ 2) Age: _________________
3) Gender: Male ☐ Female ☐ 4) Weight: ______________
5) Height: ____________
6) Years of Experience driving a forklift: ___________
7) Smoking Status: _______________________________



The following question will help us to better determine your level of health related concerns related to your participation in this study.

1) *Site and Symptoms:* Have you had pain in your low back (in the area shown on the diagram)?

   Yes ☐ No ☐

2) If yes, was this pain bad enough to limit your usual activities or change your daily routine for more than one day?

   Yes ☐ No ☐

3) *Sciatica:* Have you had pain that goes down the leg?

   Yes ☐ No ☐

4) If yes, has this pain spread below knee/

   Yes ☐ No ☐

5) *Frequency:* if you had a pain in your low back in the past 4 weeks, how often did you have the pain?
   On some days ☐ on most days ☐ Every day ☐

6) *Duration:* If you had low back pain in the past 4 weeks, how long was it since you had a whole month without any low back pain?

Less than 3 months ☐
3 months or more but less than 7 months ☐
7 months or more but less than 3 years ☐
3 years and more ☐

7) *Severity*: If you had low back pain in the past 4 weeks, please indicate what was the usual intensity of your pain on a scale of 0 – 10, where 0 means “no pain” and 10 means “the worst pain imaginable”? (Please circle your answer)

   0 1 2 3 4 5 6 7 8 9 10
   No pain Worst pain

Figure 3.7: Low back pain questionnaire

3.5 Data Analysis

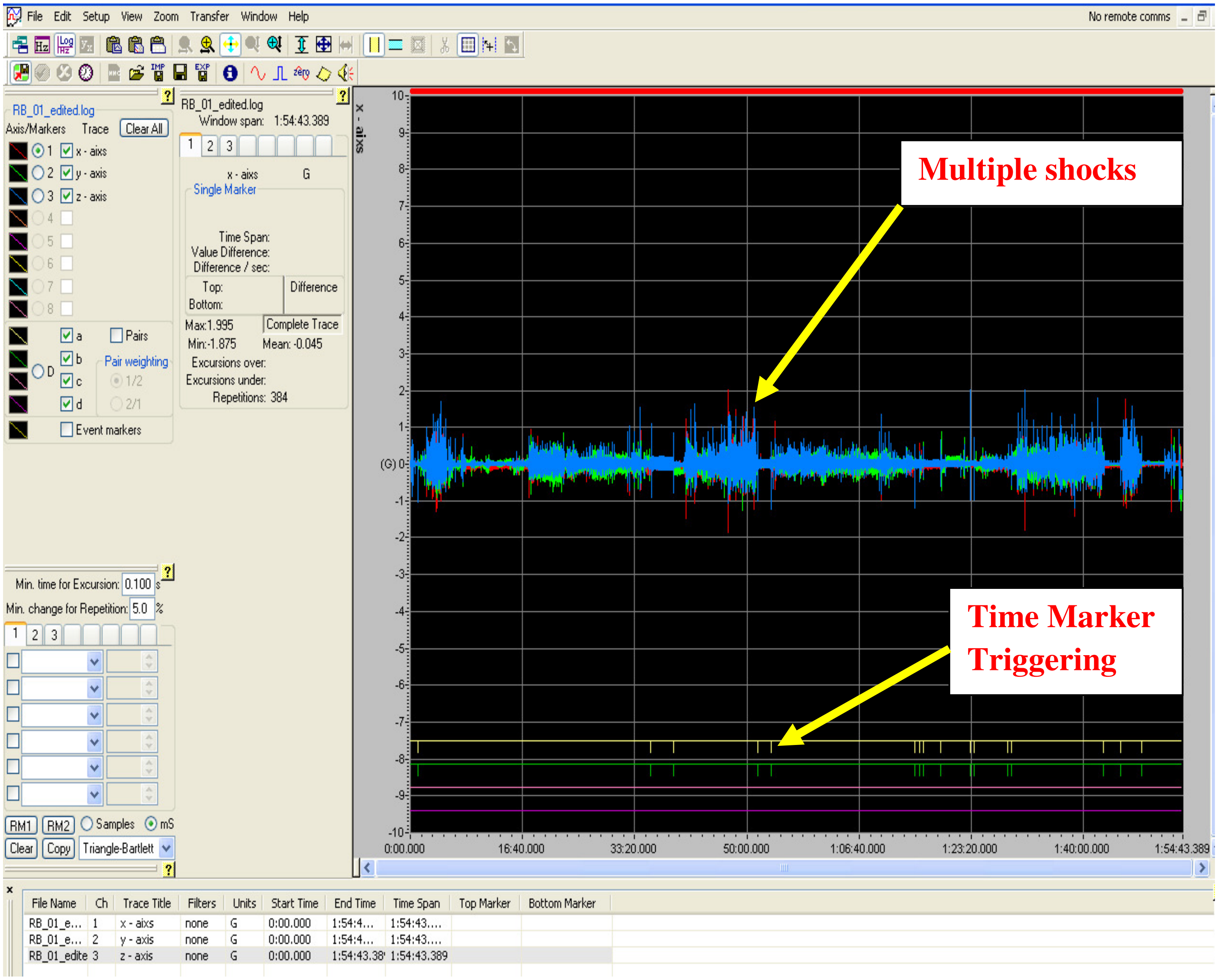
Vibration analysis was conducted in accordance with ISO 2631-1 and carried out with the Vibration Analysis Tool-Set (VATS 3.0) software (NexGen Ergonomics, Montreal, Quebec, Canada). Frequency-weighted root-mean-square (r.m.s.) accelerations (a_{wx}; a_{wy}; a_{wz}) were calculated using the appropriate weighting factors as described in ISO 2631-1 (x-axis = W_d; y-axis = W_d; z-axis = W_k). Scaling factors associated with the determination of health for seated exposure were also applied (x-axis, k=1.4; y-axis, k=1.4; z-axis, k=1.0). Frequency-weighted r.m.s. vector sum values (a_{xyz}), peak accelerations, crest factors (CF), and vibration dose values (VDV) for each axis were calculated (from frequency-weighted data) using the software. The recorded vibration data were broken down into multiple 5-minute segments for the analysis. Then the 5-minute segment values were averaged to produce a representative vibration value that had greater stability (Eger et al., 2008).

The axis with the highest frequency-weighted r.m.s. acceleration value and VDV was selected for comparison to the ISO 2631-1 HGCZ limits associated with 8 h of daily exposure. The ISO 2631-1 standard states that the frequency-weighted r.m.s. acceleration values corresponding to the lower and upper limits of the 8-h health guidance caution zone (HGCZ) are 0.45 and 0.90 m/s^2, respectively, while the VDVs corresponding to the lower and upper limits of the 8-h HGCZ are 8.5 and 17 $m/s^{1.75}$, respectively.

ISO 2631-5 provides guidance for assessment of health effects to the lumbar spine associated with vibration exposure containing multiple shocks. This vibration analysis was conducted in accordance with ISO 2631-5 procedures using VATS 3.0 software. An example of an un-weighted r.m.s. acceleration data for the z-axis is shown in figure 3.8, to illustrate the presence of multiple shocks during operation of a forklift. This data were then used to determine the daily equivalent static compression dose, S_{ed}, which in turn was used to compute the R factor. Detailed calculations can be found in the ISO 2631-5 documentation, while a summary was provided in the earlier section 2.3. Rankings (high; moderate; low) for predicted health risks were determined for each subject (forklift operator) based on HGCZ limits for A(8), and VDV total values published in ISO 2631-1. Ratings were also performed for S_{ed} limits established for probability of an adverse health effects as reported in ISO 2631-5. Table 3.4 shows the Summary of limits associated with different levels of predicted "health risk" according to "HGCZ" values discussed in ISO 2631-1 and ISO 2631-5.

Table 3.4 Summary of limits associated with different levels of predicted "health risk" according to "HGCZ" values discussed in ISO 2631-1 and ISO2631-5 (Eger et al. 2008)

ISO 2631-1 assessment of adverse health effects	Terminology to describe predicted health risks	**ISO 2631-1**	
		A(8) m/s^2 r.m.s	VDV_{total} $m/s^{1.75}$
For exposure below the zone (HGCZ), health effects have not been clearly documented and/or objectively observed	Low	<0.45	<8.5
In this zone (HGCZ), caution with respect to potential health risks is indicated	Moderate	0.45-0.9	8.5-17
Above this zone (HGCZ), health risks are likely	High	>0.9	>17
ISO 2631-5 assessment of adverse health effects	Terminology to describe predicted health risks	**ISO 2631-5**	
		S_{ed} MPa	R factor
Low probability of adverse health effect	Low	<0.5	<0.8
Moderate probability of adverse health effect	Moderate	0.5-0.8	0.8-1.2
High probability of adverse health effect	High	>0.8	>1.2



RB_01_edited.log

Window span: 1:54:43.389

Max: 1.995

Min: -1.875

Mean: -0.045

Repetitions: 384

Min. time for Excursion: 0.100 s

Min. change for Repetition: 5.0 %

Triangle-Bartlett

File Name	Ch	Trace Title	Filters	Units	Start Time	End Time	Time Span	Top Marker	Bottom Marker
RB_01_e...	1	x - aixs	none	G	0:00.000	1:54:4...	1:54:43....		
RB_01_e...	2	y - axis	none	G	0:00.000	1:54:4...	1:54:43....		
RB_01_edite	3	z - axis	none	G	0:00.000	1:54:43.38'	1:54:43.389		

Figure 3.8: The presence of multiple shocks when forklift operators are exposed to WBV

A one-third octave frequency band analysis was carried out for different road profiles for forklifts driven inside the shop floor, forklifts driven outside, and the forklifts driven both inside an outside of the shop floor. The frequency vs. frequency-weighted acceleration r.m.s value graphs were plotted for the dominant vertical z-axis. The rationale of performing a frequency band analysis as a function of different road profile was to determine the dominant frequency where the highest vibration magnitudes occurred. Frequency band analysis would also indicate the values for frequency-weighted acceleration r.m.s values, which would signify the worst road profile (inside, outside and inside-outside).

A track type analysis was carried out in order to identify the effect of driving surface on transmitting the vibration levels to the forklifts. Forklifts driven on different surfaces may have dissimilar values of vibrations. For example, a forklift driven on a rough surface may have vibration levels that are considerably higher compared to a forklift driven on a smooth concrete surface (e.g. inside the shop floor). In the current study, the forklifts were driven inside the shop floor on a smooth concrete track, outside the shop floor on a rough track and inside-outside the shop floor. The analysis consisted of descriptive statistics (e.g. mean and standard deviation) of the vibration measures (A (8), VDV, S_{ed}, R factor) for forklifts driven on different surfaces.

3.6 Forklift Analysis

In the current study different manufacturer and models of forklifts were used for data collection. These forklifts had different specifications in terms of model, manufacturer, tire type, engine type, seat adjustments, and load capacity. Also these forklifts were driven on different terrains (inside, outside and inside-outside the shop). These specifications are presented in the results section to determine which forklifts had elevated vibration exposure levels. This forklift specification analysis would allow a better understanding of the aspects of the forklift that may contribute to elevated or lower exposure levels of vibration.

3.7 Statistical Analysis

A statistical analysis was performed for the health risk severity obtained from the ISO 2631-1 and ISO2631-5 analysis. The nonparametric Sign test was used to compare the health risk estimated between the ISO 2631-1 and ISO 2631-5 analysis. The sign test is applicable in the case when two related samples are present in order to establish that the two conditions are different (Siegel and Castellan, 1988.). The sign test was used for this research because in this case two related samples (ISO 2631-1 and ISO 2631-5 measures) were taken into account. Hence, a pair was formed between the two measures from the two standards. For example, a pair was formed between A (8) and S_{ed}, which were the measures of ISO 2631-1 and ISO 2631-5 respectively. Similarly pairs between A (8) and the R factor, VDV and S_{ed}, and VDV and R factor were formed. The signs were obtained from the analyzed tables (from results section) showing the health risk in order to perform the sign test. Depending upon the signs obtained from the paired tables, conclusion of similarity between the standard measures was drawn. For the body part discomfort survey before and after the vibration data collection, a dependent sample t-test was performed for each body part. A significance level of $\alpha = 0.05$ was utilized for all statistical tests performed.

CHAPTER 4

4.0 RESULTS

4.1 Summary of Demographic and Low Back Questionnaire

Table 4.1 shows the summary of the demographic and low back pain questionnaire for all seven subjects who participated in this study.

Table 4.1: Summary of demographic questionnaire for all seven subjects.

Subject	Gender	Age	Smoking Status	Site & Symptoms of LBP	Sciatica (pain going in leg)	Frequency	Duration	Severity
1	Male	52	None	Yes	No	Some days	>1year	2
2	Male	52	None	No	No	-	-	1
3	Male	49	None	No	No	-	-	-
4	Male	52	Yes	Yes	Yes	Most days	3 months	4
5	Male	49	Yes	Yes	Yes	Most days	3 months	7
6	Male	54	Yes	Yes	Yes	Most days	3 months	8
7	Male	45	None	Yes	Yes	Every day	1 year	4

The majority of the subjects (five out of seven) reported symptoms of low back pain, with four of the five also indicating experiencing sciatica, or pain radiating down the leg. The subjects that indicated experiencing sciatica also appeared to rate the severity of their low back pain higher (ranging from 4-8) compared to those who didn’t indicate sciatica (rating of 2). For three subjects, the frequency of having the low back pain was “on most days” while one subject had low back pain “every day”.

4.2 Summary of Body Part Discomfort Survey

Figure 4.1 shows the level of discomfort for different body parts according to the body part discomfort survey conducted before and after data collection. From this figure the discomfort in shoulder, low back and hip/thigh increased considerably compared to the other body parts. The body parts with increase in discomfort are highlighted with (***). Table 4.2 shows the detailed values/scores for discomfort before and after rated by the subjects participated in this study. This table also shows the dependent sample t-test values for all body parts. According to this table also shoulder, low back and hip/thigh show a significant increase in discomfort. The p values are also presented in the same table 4.2.

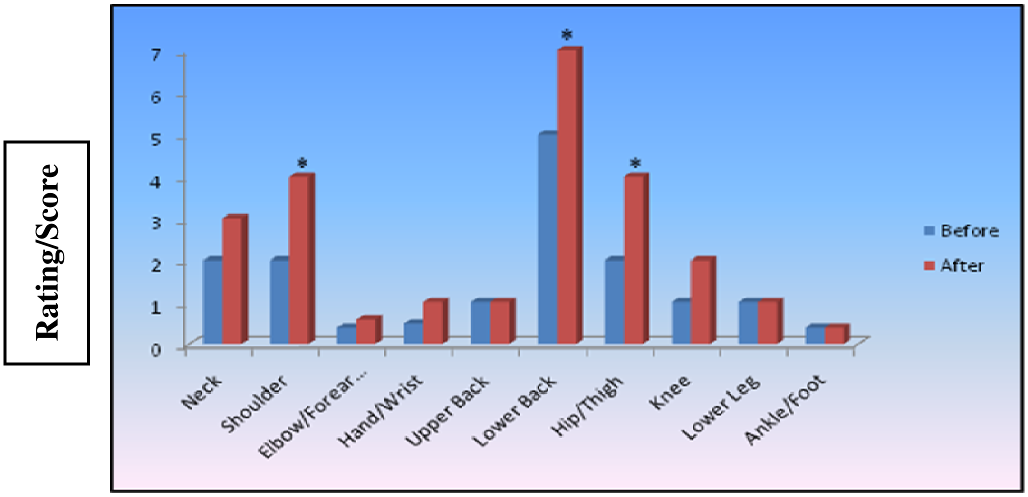


Figure 4.1: Mean body part discomfort before and after recording vibration data (* indicates significant difference at p<= 0.05 in ascertain level before and after vibration recording)

Table 4.2: Paired Two Sample for Means (t-test) for each body part discomfort

Discomfort Area	**Rating Score**	**Discomfort Area**	**Rating Score**	**t-value** **p-value**
Before		**After**		
Neck	2.0	Neck	3.0	t = 1.9432 p= 0.0941
Shoulder	2.0	Shoulder	4.0	t = 6.0000 p= 0.0009
Elbow/Forearm	0.4	Elbow/Forearm	0.6	t = 1.0000 p= 0.3555
Hand/Wrist	0.5	Hand/Wrist	1.0	t = 1.0000 p= 0.3555
Upper Back	1.0	Upper Back	1.0	t = 0.0000 p= 0.1843
Lower Back	5.0	Lower Back	7.0	t = 4.0762 p= 0.0065
Hip/Thigh	2.0	Hip/Thigh	4.0	t = 5.2842 p= 0.0018
Knee	1.0	Knee	2.0	t = 1.5492 p= 0.1723
Lower Leg	1.0	Lower Leg	1.0	t = 1.0000 p= 1.0000
Ankle/Foot	0.4	Ankle/Foot	0.4	t = 0.0000 p= 1.0000

4.3 Frequency Analysis

Figure 4.2 shows a summary of the 1/3 octave band frequency-weighted acceleration value for dominant z-axis of all seven subjects for different road profiles on which the forklifts were driven. The dominant frequency-weighted r.m.s. acceleration was occurred in the z-axis at frequency of 8 Hz for the forklifts driven outside the shop floor. The forklifts which were driven inside or inside and outside were dominant at a frequency range of 4 – 5 Hz.

The z-axis frequency weighted r.m.s acceleration for forklifts driven outside were observed with a magnitude of greater than 0.80 m/s^2 which were higher compared to forklifts driven inside and inside-outside the shop.

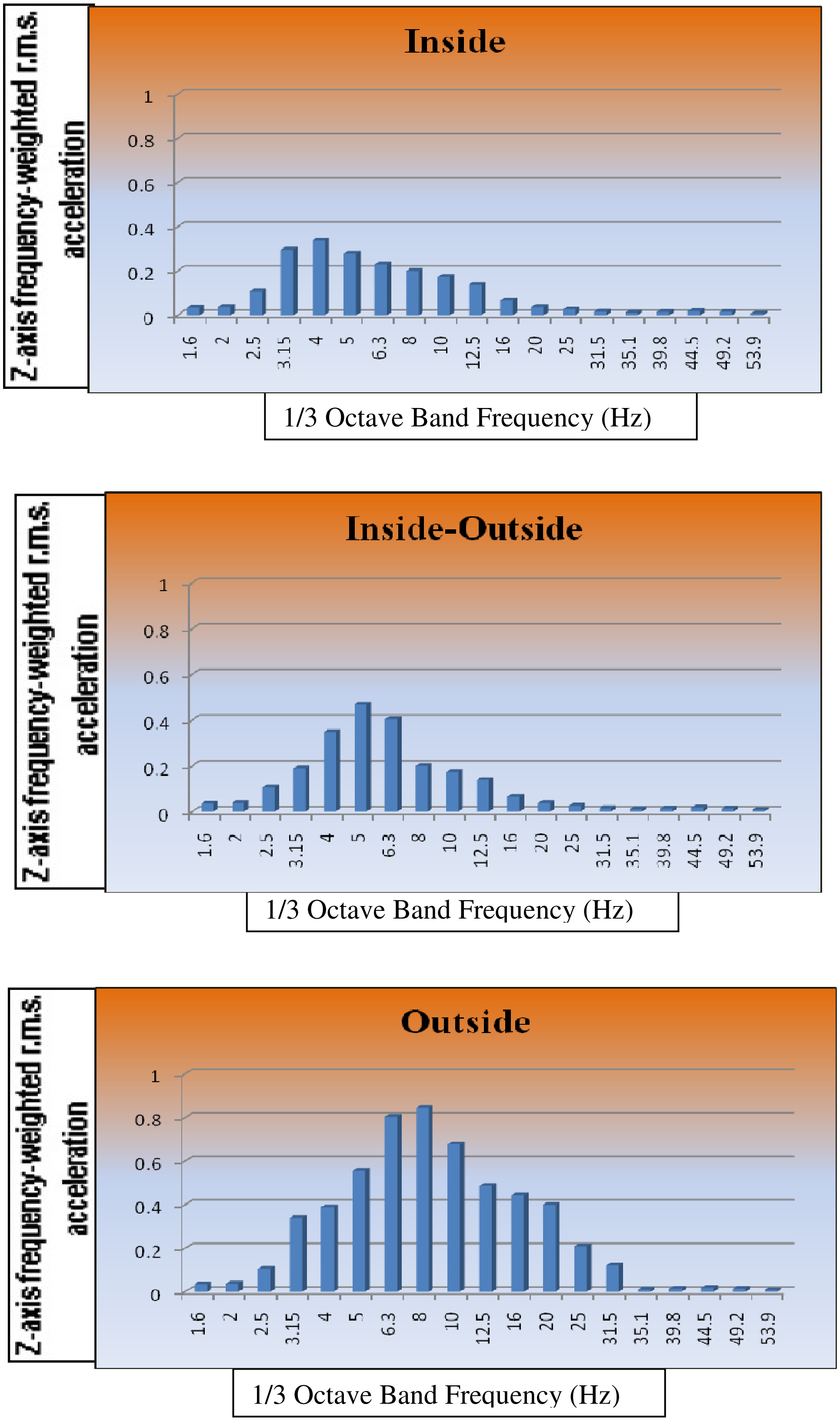


Figure 4.2: Summary of 1/3 octave band frequency-weighted r.m.s acceleration.

4.4 Track type analysis

Figure 4.3 shows the different road profile corresponding to the values of the respective measures of ISO 2631-1 and ISO 2631-5. From this figure it appears that the forklifts driven outside the shop floor on irregular surface resulted in higher ISO vibration-related values compared with forklifts driven inside the shop floor. For A (8), as a measure of analysis the frequency-weighted r.m.s accelerations (m/s^2) for the forklifts driven outside appear to be higher than the forklifts driven inside and inside-outside the shop floor. Similarly, for VDV, R factor and S_{ed} as a measure of analysis, the values were always higher for the forklifts driven outside the shop.

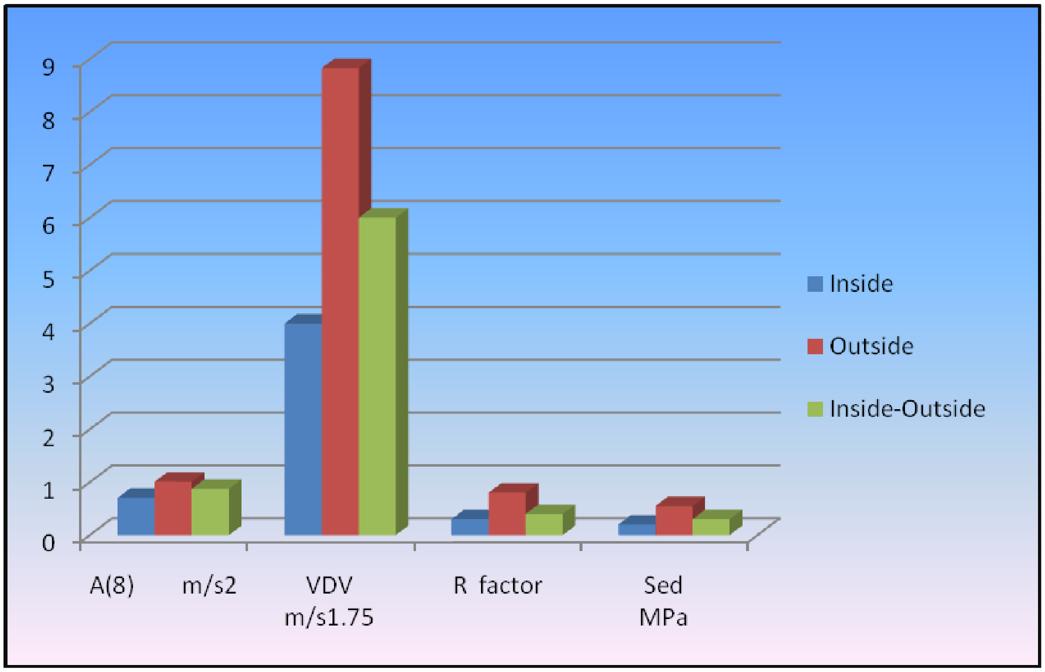


Figure 4.3: Different track types with equivalent ISO measures

4.5 ISO 2631-1 analysis

Table 4.3 shows a summary of the health risks to forklift operators according to ISO 2631-1 HGCZ boundaries based on the estimated 8-h frequency-weighted r.m.s acceleration value A(8). Table 4.3 also includes the forklift manufacturer model, forklift capacity, road profile (whether forklift driven inside or outside the shop floor), duration of vibration data collected and the frequency-weighted acceleration values. The terms high, low and moderate were used to describe the probability of adverse health effects. The acceleration values of the dominant vertical axis (z-axis) were used to determine the health risk exposure levels as the magnitude of r.m.s were higher compared to x-axis and y-axis.

After comparing the values of frequency-weighted accelerations with the table 3.4, it is estimated that the forklift operators (subjects five and six) are exposed to a high probability of adverse health effects on the lumbar spine according to the HGCZ as the frequency-weighted r.m.s acceleration in z-direction is 1.0741 and 0.9325 m/s^2, which exceeds the HGCZ limit value of 0.9 m/s^2. Subjects one to three and seven fall with the moderate zone of HGCZ (0.45 – 0.9 m/s^2). Subject four fall below the HGCZ (< 0.45 m/s^2).

When the VDV_{total} values were used to predict health risks, two forklift operators were found to be in the moderate zone (between 8.5 and 17 $m/s^{1.75}$) in accordance to HGCZ (Table 4.4), whereas five subjects were found to be in the low zone (<8.5 $m/s^{1.75}$).

Table 4.3: Determination of health risk, to forklift operator, according to ISO 2631-1 HGCZ boundaries based on the estimated 8-h frequency-weighted r.m.s acceleration value A (8).

Subject	Forklift Model	Forklift Capacity	Forklift driven on surface	Drivers estimated daily exposure (h)	Duration of measurement (h:m)	Vibration magnitude on seat dominant axis) for the measured duration (m/s^2) r.m.s	ISO 2631-1 HGCZ (based on an 8 h exposure duration)
1	CAT	3-Tons	Inside-Outside	7	1:50	0.6227	Moderate
2	Mitsubishi	3-Tons	Inside-Outside	7	1:52	0.5064	Moderate
3	Mitsubishi	3-Tons	Inside-Outside	7	1:55	0.4935	Moderate
4	Hyster	3-Tons	Inside	7	1:48	0.3843	Low
5	Hyster	5-Tons	Outside	7	1:52	1.0741	High
6	CAT	5-Tons	Outside	7	1:45	0.9325	High
7	CAT	3-Tons	Outside	7	1:58	0.7582	Moderate

Table 4.4: Determination of health risk, to forklift operator, according to ISO 2631-1 HGCZ boundaries based on the estimated 8-h vibration dose value, VDV $_{total}$.

Subject	**Forklift Model**	**Forklift Capacity**	**Forklift driven on surface**	**Drivers estimated daily exposure (h)**	**Duration of measurement (h)**	**Mean VDV on seat (dominant axis) for measured duration (m/s$^{1.75}$)**	**ISO 2631-1 HGCZ (based on an 8 h exposure duration)**
1	CAT	3-Tons	Inside-Outside	7	1:50	6.3345	Low
2	Mitsubishi	3-Tons	Inside-Outside	7	1:52	5.5714	Low
3	Mitsubishi	3-Tons	Inside-Outside	7	1:55	4.5433	Low
4	Hyster	3-Tons	Inside	7	1:48	3.8264	Low
5	Hyster	5-Tons	Outside	7	1:52	9.4716	Moderate
6	CAT	5-Tons	Outside	7	1:45	8.7516	Moderate
7	CAT	3-Tons	Outside	7	1:58	8.2283	Low

4.6 ISO 2631-5 analysis

Two approaches were utilized to calculate the R factor values in this study. First, health risks for the current forklift operators, based on their individual operating profile, were considered. In the individual operating profile the parameters considered were the individuals experience of driving forklift, age at which the exposure started, number of days exposed in a year and number of hours the operator is exposed in a day driving forklift. Table 4.5 shows the summary of the ISO 2631-5 analysis according to individual operating profile for each of the forklift operators. Table 4.5 also shows the values of R factor and S_{ed} for individual operating profiles.

Second, exposure characteristics associated with a standardized forklift operator profile were utilized to determine health risks associated with lifetime exposure that a worker who operates a forklift would experience. Therefore, the same exposure history (age at first exposure = 25 years; daily exposure = 8 h; yearly exposure = 250 days; lifetime exposure = 30 years) was used to predict the R factor associated with driving for each forklift operator. Table 4.6, shows the ISO 2631-5 analysis according to the standardized operating profile of the forklift operators. According to ISO 2631-5, R factor values below 0.8 indicate a low probability of adverse health effects to the lumbar spine while values greater than 1.2 suggest a high probability of adverse effects. Similarly, a daily equivalent static compression doses (S_{ed}) below 0.5 Mpa indicates a low probability of an adverse health effect to the lumbar spine while values greater than 0.8 MPa suggest a high probability of adverse health effects.

Table 4.5: ISO 2631-5 analysis according to individual operating profile of the forklift operators

Subject	Forklift Model	Forklift driven on surface	Forklift Capacity	Current Age (years)	First exposure age (years)	Current lifetime exposure (years)	Vibration exposure profile		Calculated ISO 2631-5	
							Daily exposure (h)	Yearly exposure (days)	S_{ed} (MPa)	R factor
1	CAT	Inside-Outside	3-Tons	52	34	12	7	250	0.34	0.42
2	Mitsubishi	Inside-Outside	3-Tons	52	40	13	7	250	0.24	0.31
3	Mitsubishi	Inside-Outside	3-Tons	49	39	15	7	250	0.27	0.36
4	Hyster	Inside	3-Tons	52	32	10	7	250	0.19	0.23
5	Hyster	Outside	5-Tons	49	28	20	7	250	0.56	0.85
6	CAT	Outside	5-Tons	54	29	11	7	250	0.54	0.81
7	CAT	Outside	3-Tons	45	27	18	7	250	0.50	0.73

The calculated equivalent daily static compressive stress on the lumbar spine, S_{ed}, values were compared to the lower and upper boundary values associated with low and high probabilities of adverse health effects (Table 3.4). Two forklift operators (subject five and six) who drove the forklifts outside the shop had S_{ed} values that placed them at or just above the cut-off associated with a moderate probability for adverse health effects. Therefore according to table 4.5, the subjects five, six and seven may be exposed to moderate risk of adverse health effect on lumbar spine with continued exposure at these levels. Subjects one to four fall within the lower limit of HGCZ according to ISO 2631-5. For the R factor, two of the subjects who drove outside had R factor values which placed them in the moderate probability category for adverse health effect to the lumbar spine (0.8 to 1.2), whereas the other four subjects were within the low probability range (< 0.8).

Table 4.6: ISO 2631-5 analysis according to a standardized operating profile of the forklift operators.

Subject	**Forklift Model**	**Forklift driven on surface**	**Forklift Capacity**	**Lifetime exposure (years)**	**Vibration exposure profile**		**Calculated ISO 2631-5**	
					Daily exposure (h)	**Yearly exposure (days)**	**S_{ed} (MPa)**	**R factor**
1	CAT	Inside-Outside	3-Tons	30	8	250	0.34	0.43
2	Mitsubishi	Inside-Outside	3-Tons	30	8	250	0.24	0.31
3	Mitsubishi	Inside-Outside	3-Tons	30	8	250	0.28	0.36
4	Hyster	Inside	3-Tons	30	8	250	0.23	0.27
5	Hyster	Outside	5-Tons	30	8	250	0.56	0.86
6	CAT	Outside	5-Tons	30	8	250	0.53	0.83
7	CAT	Outside	3-Tons	30	8	250	0.51	0.77

Table 4.6 shows the ISO 2631-5 analysis according to a standardized operating profile of forklift operators. The life time exposure to WBV was considered to be thirty years with daily exposure of eight hours of work and 250 days in a year. If one compares the standardized operating profile and the individual specific operating profile, the values of R factor and S_{ed} values are relatively similar, although some forklift operators have minor increases in the standardized operating profile for a forklift operator. This small increase in values of R and S_{ed} may be due to the typical parameters considered (age at first exposure = 25 years; daily exposure = 8 h; yearly exposure = 250 days; lifetime exposure = 30 years). As in the individual operating profile the years of exposure to vibration vary for every subject.

4.7 Comparison of ISO 2631-1 and ISO 2631-5

Table 4.7 shows the comparison between the two methods, ISO 2631-1 (1997) and ISO 2631-5 (2004). According to A (8), which is a measure of ISO 2631-1, subjects five and six appear to be at a high risk for the lumbar spine, whereas according to VDV which is also a measure of ISO 2631-1, subjects five and six appear to be at a moderate risk for lumbar spine. When the R factor and S_{ed}, which are the measures of ISO 2631-5, subjects five and six appear to be at a moderate risk for lumbar spine. Also, according to VDV, R factor and S_{ed} values the results appear to be similar for all the subjects except, R factor placed for subject seven at low risk of health on lumbar spine, while VDV is being a measure of ISO 2631-1 and R factor or S_{ed} being the measures of ISO 2631-5. The health effects estimated by ISO 2631-5 were typically lower when compared to ISO 2631-1 with A (8) as a measure for analysis.

Table 4.7: Comparison between ISO 2631-1 (1997) and ISO 2631-5(2004).

Subject	**Forklift Model**	**ISO 2631-1 method**				**ISO 2631-5 method**			
		Frequency-weighted r.m.s method		**VDV method**		**S_{ed} MPa**	**Health Risk Severity**	**R factor**	**Health Risk Severity**
		A(8) m/s^2	**Health Risk Severity**	**VDV_{total} $m/s^{1.75}$**	**Health Risk Severity**				
1	CAT	0.6227	Moderate	6.3345	Low	0.34	Low	0.42	Low
2	Mitsubishi	0.5064	Moderate	5.5714	Low	0.24	Low	0.31	Low
3	Mitsubishi	0.4935	Moderate	4.5433	Low	0.27	Low	0.36	Low
4	Hyster	0.3843	Low	3.8264	Low	0.19	Low	0.23	Low
5	Hyster	1.0741	High	9.4716	Moderate	0.56	Moderate	0.85	Moderate
6	CAT	0.9325	High	8.7516	Moderate	0.54	Moderate	0.81	Moderate
7	CAT	0.7582	Moderate	8.2283	Low	0.50	Moderate	0.73	Low

Table 4.8 shows detailed forklift specifications to identify for elevated exposure levels. In this table detailed specifications such as manufacturer of forklift, model of forklift, engine driven, tire type, seat type, and forklift capacity of forklifts are shown which were used for data collection in the current study. Different manufacturer of forklifts with different models were used for data collection. Two forklifts which showed elevated exposure levels had a diesel engine on the forklift, whereas other five forklifts had propane driven engines. Hence, forklifts having diesel engines may possibly report high exposure levels of vibration. Also the two forklifts which exceeded the HGCZ were having a high capacity of 5-tons while other five forklifts were 3-ton forklifts. All seven forklifts had solid tires on it, but only one forklift had a soft rubber. This one forklift was identified with exposure levels of vibration below the HGCZ from ISO 2631. This table also shows which forklifts were driven on which terrain. There were different surface profiles on which the forklifts were driven such as inside, outside and inside-outside the shop.

Table 4.8: Detailed forklift specifications for elevated exposure levels.

Subject	**Forklift Manufacturer**	**Forklift Model**	**Engine**	**Tire**	**Seat**	**Forklift Capacity**	**Forklift driven on surface**
1	CAT	B471G 20LP	Propane Gas	Solid	Full-Suspension Cushioned	3-Tons	Inside-Outside
2	Mitsubishi	FG 40K LP	Propane Gas	Solid	Full-Suspension Cushioned	3-Tons	Inside-Outside
3	Mitsubishi	H40 FTS	Propane Gas	Solid	Full-Suspension Cushioned	3-Tons	Inside-Outside
4	Hyster	H50 XM	Propane Gas	Solid-Soft rubber	Full-Suspension Cushioned	3-Tons	Inside
5	Hyster	H100 FT	Diesel	Solid	Full-Suspension Cushioned No armrest	5-Tons	Outside
6	CAT	DP 50	Diesel	Solid	Full-Suspension Cushioned No armrest	5-Tons	Outside
7	CAT	GP 20K	Propane Gas	Solid	Spring-Adjusted	3-Tons	Outside

From table 4.8 the forklifts which were driven outside the shop had highest level of vibration levels. These forklifts had a diesel driven engine with 5 ton capacity. The forklift which was driven inside the shop had lowest vibration exposure levels, and this forklift was provided with a soft rubber tires. The forklifts driven inside-outside the shop were between the moderate ranges of exposure levels. These forklifts had similar characteristics with solid tires and full suspension seats.

4.8 Statistical analysis for Health Severity Risk

The nonparametric Sign test was used for comparison of the health risk estimates between ISO 2631-1 and ISO 2631-5. Table 4.8 shows the sign tests and the summary of the sign test indicating the health severity risk estimated by the A (8) and S_{ed} factors from ISO 2631-1 and ISO 2631-5, respectively.

An example is presented to show the statistical analysis using sign test. The sign test was performed at a significance level of $\alpha = 0.05$ with N being the number of subject's who showed a difference in estimated risk level between two different measures (+ or -). The null hypothesis H_0: no difference in the estimate of the level of the health effect between the ISO 2631-1 and ISO 2631-5 measures; the alternate hypothesis H_1: ISO 2631-1 and ISO 2631-5 measures result in different estimates of the level of health effect. A sign test was performed (Table 4.9) between A (8) (a measure of ISO 2631-1) and S_{ed} (a measure of ISO 2631-5). The difference between the estimated risk level between these two measures are shown with a + or – sign. If both measures show a same risk level, then it was marked as 0 and was not considered in N. From the probabilities table the value of p is determined which was found to be $p = 0.031$. This p value which is less than $\alpha = 0.05$, indicates that the null hypothesis is rejected specifying that the two measures estimated different risk levels. Table 4.9 also shows a table with tally for these two measures, the A (8) and S_{ed}. The tallies were marked according to the risk levels shown by the two measures. In table 4.10 a sign test was performed between the A (8) and R factor (a measure of ISO 2631-5). The p value was observed to be $p = 0.016$, which is less than $\alpha = 0.05$, indicating that the null hypothesis is rejected. Therefore, ISO 2631-1 and ISO 2631-5 estimated different levels of adverse health effects on the lumbar spine. Similarly, in table 4.11 sign test were performed between VDV (a measure of ISO 2631-1) and S_{ed}. From this sign test one negative sign and six zeros were observed. In this case p value was not determined because less than one subject showed a difference in signs. In table 4.12 when a sign test was performed between VDV and the R factor not a single subject showed a difference in sign. Therefore, no p value was determined.

Table 4.9: The Sign tests and the summary of the sign test indicating the health severity risk from the A (8) and S_{ed} factors from ISO 2631-1 and ISO 2631-5, respectively.

Sign test

Subject	ISO 2631-1 A(8)	ISO 2631-5 S_{ed}	Sign
1	Moderate	Low	+
2	Moderate	Low	+
3	Moderate	Low	+
4	Low	Low	0
5	High	Moderate	+
6	High	Moderate	+
7	Moderate	Moderate	0

Summary of sign test

Health Severity Risk		ISO 2631-5 S_{ed}		
		Low	Moderate	High
ISO 2631-1 A(8)	Low	1		
	Moderate	3	1	
	High		2	

Table 4.10: Sign tests and the summary of the sign test indicating the health severity risk from the A (8) and R factors from ISO 2631-1 and ISO 2631-5, respectively.

Sign test

Subjects	ISO 2631-1 A(8)	ISO 2631-5 R	Sign
1	Moderate	Low	+
2	Moderate	Low	+
3	Moderate	Low	+
4	Low	Low	0
5	High	Moderate	+
6	High	Moderate	+
7	Moderate	Low	+

Summary of sign test

Health Severity Risk		ISO 2631-5 R		
		Low	Moderate	High
ISO 2631-1 A(8)	Low	1		
	Moderate	4		
	High		2	

Table 4.11: Sign tests and the summary of the sign

test indicating the health severity risk from the VDV and S_{ed} factors from ISO 2631-1 and ISO 2631-5, respectively.

Sign test

Subjects	ISO 2631-1 VDV	ISO 2631-5 S_{ed}	Sign
1	Low	Low	0
2	Low	Low	0
3	Low	Low	0
4	Low	Low	0
5	Moderate	Moderate	0
6	Moderate	Moderate	0
7	Low	Moderate	-

Summary of sign test

Health Severity Risk		ISO 2631-5 S_{ed}		
		Low	Moderate	High
ISO 2631-1 VDV	Low	4	1	
	Moderate		2	
	High			

Table 4.12: Sign tests and the summary of the sign test indicating the health severity risk from the VDV and R factor from ISO 2631-1 and ISO 2631-5, respectively.

Sign test

Subjects	ISO 2631-1 VDV	ISO 2631-5 R	Sign
1	Low	Low	0
2	Low	Low	0
3	Low	Low	0
4	Low	Low	0
5	Moderate	Moderate	0
6	Moderate	Moderate	0
7	Low	Low	0

Summary of sign test

Health Severity Risk		ISO 2631-5 R		
		Low	Moderate	High
ISO 2631-1 VDV	Low	5		
	Moderate		2	
	High			

CHAPTER 5

5.0 DISCUSSION

The aims of the current study were to quantify WBV among forklift drivers using ISO 2631-1 and ISO 2631-5, and to compare the levels of WBV exposure using these two standards. In the current study, forklifts were driven on different surfaces (inside, outside and inside-outside the shop). The forklifts driven outside the shop exceeded (frequency-weighted r.m.s acceleration in z-axis) the HGCZ (>0.9 m/s^2) of ISO 2631-1, for the measure A (8), while these same forklifts were identified to be within the moderate range (8.5 - 17 m/s$^{1.75}$) of the HGCZ for ISO 2631-1 for the measure vibration dose value (VDV). Similarly, forklifts driven outside the shop were in the moderate range of HGCZ for ISO 2631-5, for the measures S_{ed} (0.5 – 0.8 MPa) and the R factor (0.8 – 1.2). The forklifts driven inside the shop were below the HGCZ for all the measures of the two ISO standards. Forklifts driven inside-outside the shop were in the moderate range of A (8) measure. According to ISO 2631-5 measures these forklifts were below the HGCZ and similar result were obtained according to VDV, a measure of ISO 2631-1.

Similar results were also reported by Cann et al. (2004) when they measured exposure levels experienced by transport truck operators to determine whether operator's exposure exceeded the ISO 2631-1 WBV guidelines. A significant relationship between the rough road condition (e.g. potholes, irregular surfaces, bumps) and frequency-weighted r.m.s accelerations ($p<0.001$) for all three axes, were found when compared to a smooth road. Therefore, road condition was a significant aspect for elevated frequency-weighted r.m.s accelerations. Further, Malchaire et al. (1996) also reported similar results for the track effect. Malchaire et al. (1996) found that track effect had the greatest affect since the difference between the acceleration on smooth concrete and on rough paved tracks reached 1 m/s^2 both on the seat and on the floor of the fork-lift truck. It was worth noting that, on average, the accelerations were reduced by about

0.10 m/s^2 on the seat in comparison with the floor on a very smooth concrete track and by 0.25 m/s^2 on a very rough (potholes, surface irregularities, bumps) paved track.

According to the low back questionnaire which was carried out among the participants for the current study, a majority of the subjects indicated they experienced low back pain. About 70% of the subjects were having symptoms for low back pain. In addition, 72% of the subjects reported experiencing symptoms of sciatica (a pain radiant to the leg). The subjects experiencing sciatica also reported severe pain in the low back with ratings ranging from (4 – 8) on a scale from zero to ten, zero being no pain and ten being worst pain. Accordingly, the body part discomfort survey showed a significant increase in discomfort for the low back, shoulder and hip/thigh were observed from the time before to after the vibration data were collected. For neck, elbow/forearm, hand/wrist, upper back, knee, lower leg and ankle/foot no statistically significant increase in discomfort was observed. The discomfort levels and percent of operators who experienced low back discomfort is similar in this study compared to previous studies.

Kittusamy and Buchholz (2004) found that, among operators driving construction equipment for eight hours a day and being exposed to WBV, approximately 45% of operators reported low back pain from a population of 149 subjects. The prevalence in the younger group (20–29 years) for low back pain was observed to be 35% while for the older group (50–59 years) the prevalence was observed to be 67%. The authors concluded that when exposed to WBV for long-term morphological changes (change in shape, structure or pattern of the bones or organs of low back) in the lumbar spine are likely to appear. Shinozaki et al. (2001) reported a 63% prevalence of low back pain among forklift operators, which was significantly higher when compared to the non-driving blue-collar workers (32%). Boshuizen et al. (1990) found that younger drivers (<35 years) had a higher prevalence (68%) of short and long lasting back pain compared to a reference group of non-drivers (25%). Magnusson et al. (1998) reported 50% prevalence of LBP among a group of construction vehicles, industrial lorries, mining vehicles and military vehicle compared to a non-drivers group. Hoy et al. (2005) also reported that low back pain was more prevalent in operators who drove forklifts than those operators who do not drive forklifts.

In the current study, the dominant frequency-weighted r.m.s. acceleration occurred in the z-axis at a frequency of 8 Hz for forklifts driven outside the shop. The dominant frequencies for forklifts driven inside were observed to be 4 Hz while forklifts driven inside-outside the shop were observed to be between 5 – 6.5 Hz. Similar results were found by Eger et al. (2008) who identified for load haul dump vehicles the dominant frequency-weighted r.m.s. acceleration occurred in the z-axis for five load haul dump vehicles showing similar results as in the current study. Malchaire et al. (1996) also reported similar results for forklifts driven on rough track had dominant frequency-weighted r.m.s. accelerations for vertical z-axis were found to be at frequency of 4 Hz.

ISO 2631-1 (1997) defined a shock as a sudden change in acceleration that electrifies transitory vibration which occur while driving vehicles on the rough terrain. In 2004, ISO 2631-5 identified that vehicles such as forklifts, earthmoving equipment and mining equipment traveling over rough terrain likely resulted in vibration exposures with mechanical multiple shocks. According to an A (8) analysis (Table 4.3), two forklifts operators in the current study were above the HGCZ limit established from ISO 2631-1, while according to the VDV_{total} (Table 4.4), the same two forklifts were identified to be within the moderate range of the HGCZ limit. The results obtained by Hoy et al. (2005) for forklifts were consistent with the current results. They reported acceleration A (8) values for z-axis to be 0.32 - 0.73 m/s^2, while for x- and y-axis the values ranged from 0.18 – 0.44 m/s^2 and 0.17 – 0.50 m/s^2 respectively. Malchaire et al. (1996) also reported similar results to the current study with frequency-weighted r.m.s. accelerations A (8) to be 1.77 m/s^2 placing forklift operators above the HGCZ as the value exceeds 0.9 m/s^2. This elevated r.m.s. value was due a very rough concrete track on which the forklifts were driven.

The current results were also consistent with Eger et al. (2008) in which the mean A (8) values for load haul dump vehicles were found to be 1.20 m/s^2 which was above the HGCZ, while the mean VDV value was found to be 6.55 m/s$^{1.75}$ which was below the HGCZ. Results from Salmoni et al. (2008) for vehicles in the transportation industry were also consistent as the A (8) values placed the truck drivers above the HGCZ and VDV values placed the truck drivers within the moderate range of the HGCZ from ISO 2631-1.

ISO 2631-5 (2004) is epidemiologically based but not yet validated. Thus, Alem (2005) suggested that the boundary values of S_{ed} and R factor should be observed from time to time and modified as new data is being presented. The present study is limited with a small sample size and would not be suitable to suggest the lower boundaries for S_{ed} and R factor. Therefore, future research is needed in validating the new standard (ISO 2631-5) epidemiologically, in order to predict the adverse health effects on the lumbar spine or for recommending the boundaries for low and high probabilities of injury risk to the lumbar spine. In addition to this, biomechanical models should be considered to validate ISO 2631-5, as the boundary levels for low and high probabilities of adverse health effects were originally established according to biomechanical data available for lumbar spine vertebrae strength and failure (Adams et al. 1996).

In the current study, according to the individual operating profile of the forklift operators, the ISO 2631-5 analysis showed that subjects were always below and within the moderate range of HGCZ indicating low or moderate adverse health effect on the lumbar spine (Table 4.5). This was consistent with Eger et al. (2008) who found that for load haul dump vehicles the results from an ISO 2631-5 analysis placed the LHD operators below or in the moderate range of HGCZ. Cooperrider and Gordon (2008) found similar results in their study for locomotive shock and impact evaluation with ISO 2631-1 and ISO 2631-5, and showed that the S_{ed} values obtained for the locomotives travelling from New York to California were observed to be 0.123 to 0.434 MPa, indicating a low probability of an adverse health effect if the daily dose is less than 0.5 MPa. The VDV values for the same locomotives were observed to be between 2.68 to 9.33 $m/s^{1.75}$, indicating a moderate probability of adverse health effects on the lumbar spine.

The results obtained from Johanning et al. (2006) from their railroad locomotive study in observing that the ISO 2631-5, suggested low probability risk of adverse health effects on the lumbar spine. The S_{ed} values obtained were in the range of 0.11 to 0.79 MPa and the R factor range was observed to be 0.12 to 0.92, indicating a low to moderate adverse health effect on lumbar spine. The A (8) values for the same locomotive appeared to be 0.65 for the z-axis, indicating moderate risk according to HGCZ. In the current study when a sign test was performed S_{ed}, R factor and VDV showed similar results for low adverse health effects on the lumbar spine which was consistent with the other authors Eger et al. (2008), Cooperrider and Gordon (2006), and Johanning et al. (2006).

Further, Alem (2005), reported high predicted health risks on the lumbar spine based on S_{ed} values rather than VDVs. Alem compared vibration profiles which were selected only from an Army database. Alem also suggested, the lower boundary of the HGCZ, presented in Annex B of ISO 2631-1 (1997), should be $3.5m/s^{1.75}$ and the upper boundary should be $4.8m/s^{1.75}$. If these new boundaries suggested by Alem were considered, the S_{ed} values which indicated high injury risk to lumbar spine would be consistent with the VDVs which also indicated high injury risk to the lumbar spine. However, the boundary values of HGCZ should be studied periodically and modified if new data were suggested.

Eger et al. (2008) identified, the discrepancies in predicted health risks on the lumbar spine according to ISO 2631-1 and ISO 2631-5 were likely due to differences in weighting factors (the ISO 2631-1 frequency weightings vs. weightings applied in the spinal model in ISO 2631-5) applied to the raw vibration signals. Furthermore, the results and conclusions regarding adverse health effects on the lumbar spine to forklift operators should be made based on the measures used from the standards.

The characteristics of the forklifts such as tire type, seat type capacity of the forklift had a effect on exposure levels of vibration. The results from the current study were similar with Malchaire et al. (1996). In the current study forklifts with high capacity (5-tons) and solid tires had higher exposure levels of vibration (1.01 m/s^2) when compared to the forklifts with less capacity (3-tons). Similar results were estimated by Malchaire et al. (1996) for forklift with high capacity (4-ton) had higher exposure levels (1.69 m/s^2). Forklifts with anti-vibration seats were observed with less r.m.s. acceleration values (1.29 m/s^2) when compared to a normal (without) seat (1.90 m/s^2). In the current study one forklift was provided with a spring adjusted seat and the r.m.s. acceleration were observed to be less when compared to the normal seat (without spring adjustment). Shinozaki et al. (2001) identified that if forklifts are provided with pneumatic tires and anti-vibration seats the vibration levels can significantly be reduced.

In summary, the current results were similar with previous articles (Eger et al. (2008), Cooperrider and Gordon (2008) and Johanning et al. (2006). Eger et al. (2008) identified for load haul dump vehicles that ISO 2631-5 measures always showed a lower adverse health effects on the lumbar spine when compared to ISO 2631-1 measures. Particularly R factor (a measure of

ISO 2631-5) always showed a lower health risk compared to S_{ed} which is also a measure of ISO 2631-5. In the current study also R factor estimated lower health risks levels compared to S_{ed}. Cooperrider and Gordon (2008) showed similar results to the current study, that VDV and S_{ed} estimated lower health risk effects on the lumbar spine for North American locomotives. In the current study the VDV and S_{ed} estimated similar (lower) risk levels for the forklifts compared to A (8) measure. Similarly Johanning et al. (2006) identified for railroad locomotives that VDV and S_{ed} estimated similar results which were lower than A (8). Further, the R factor always estimated lower adverse health effects on the lumbar spine when compared to S_{ed} and VDV.

Limitations of the present study were the sample size tested was small. Due to limited resources (limited availability of forklifts and full time workers) all the forklift vehicles were not measured for WBV. This study was performed at an aircraft manufacturing company among forklift operators that were exposed to both WBV and possibly awkward postures including static sitting and lifting loads. However, it was not clear how much of a contribution static sitting and lifting loads had on exposure levels of WBV. The load and speed of forklifts were not measured due to the limited resources. As the load on forklift and speed of forklift change (reduced or increase) the exposure levels of WBV may also change. Hence, these factors may be critical and important to measure. Thus, it may be valuable to perform a study with measured loads on forklifts and speeds of the forklifts while collecting data.

CHAPTER 6

6.0 Conclusion

In summary, conclusions reached from this study were: 1) Initial field measurements indicated that the magnitudes of frequency-weighted acceleration r.m.s values in vertical z-axis are always higher than compared to x-axis and y-axis, 2) vibration exposure during the operation of the forklift resulted in vibration levels above or within the HGCZ limit for an eight hour exposure duration according to A(8) method, 3) two forklift operators were above the HGCZ limit according to ISO 2631-1 when compared with A (8) values, while four forklift operators were within the moderate HGCZ limit, 4) vibration levels when compared with ISO 2631-5 the R factor indicate that the two forklift operators and S_{ed} values indicate three forklift operators are at the moderate risk of having adverse health effect on lumbar spine, respectively, 5) forklifts driven outside the shop were identified to be above the HGCZ limit while the forklifts driven inside the shop were identified to be within the HGCZ limit according to ISO 2631-1 and ISO 2631-5, 6) health risks predicted by the ISO 2631-5 criteria were always lower than the risks predicted by ISO 2631-1 criteria, particularly when A(8) and S_{ed} and R factor measures were compared, 7) according to body part discomfort survey conducted before and after recording the vibration data, there was an significant increase in discomfort for low back, shoulder hip/thigh and neck.

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APPENDIX

WICHITA STATE
UNIVERSITY
The Metropolitan Advantage

Appendix A: Consent form

Department of Industrial and Manufacturing Engineering

PURPOSE: You are invited to participate in a study involving the evaluation of exposure levels of whole – body vibration due to operation of forklift and its perceived effect on low back pain / discomfort, and user's preference for using of air cushion to reduce the exposure levels of whole – body vibration.

PARTICIPANT SELECTION: You were selected as a possible participant in this study because this study focuses on evaluation of the whole – body vibration exposure levels and interventions in forklift trucks, for which you are currently an operator of.

EXPLANATION OF PROCEDURES: If you decide to participate, you will be asked to perform your job as you normally do. An accelerometer screwed to a seat pad will be tapped to the seat of the forklift. You will be shown how the DataLOG records the whole – body vibration measurement which will be hooked on the forklift. At the end of the measurement of vibration, you will be asked to complete a short questionnaire on your opinion of the measurement of whole – body vibration, use of air cushion, any affect on comfort or fatigue to the back and any recommendations or other opinions. This questionnaire will be collected by members of the Wichita State University research team.

DISCOMFORT/RISKS: To avoid interfering with the operation of the forklift, do not pertain excess pressure on the seat pad tapped on the seat and do not stand during the measurement of vibration is progress.

BENEFITS: This research will increase our knowledge and understanding of intervention efforts for low back pain associated with prolonged sitting and exposure levels of whole – body vibration due to forklift operations.

CONFIDENTIALITY: All information obtained from this study in which you can be identified will remain confidential and will be disclosed only with your permission.

COMPENSATION OR TREATMENT: Wichita State University does not provide medical treatment or other forms of reimbursement to persons injured as a result of or in connection with participation in research activities conducted by Wichita State University or its faculty, staff, or students. If you believe that you have been injured as a result of participating in the research covered by this consent form, you can contact the Office of Research Administration, Wichita State University, Wichita, KS 67260-0007, telephone (316) 978-3285.

REFUSAL/WITHDRAWAL: Participation in this study is entirely voluntary. Your decision whether or not to participate will <u>not</u> affect your future relations with Wichita State University and/or the National Institute for Occupational Safety and Health, Spokane Research Laboratory. If you agree to participate in this study, you are free to withdraw from the study at any time without penalty.

CONTACT: If you have any questions about this research, you can contact me at: Michael J. Jorgensen, Ph.D., 120 Engineering Building, Wichita, KS, 67260-0035, (316) 978-5904. If you have questions pertaining to your rights as a research subject, or about research-related injury, you can contact the Office of Research Administration at Wichita State University, Wichita, KS 67260-0007, and telephone (316) 978-3285.

You are under no obligation to participate in this study. Your signature indicates that you have read the information provided above and have voluntarily decided to participate.

You will be given a copy of this consent form to keep.

Signature of Subject	Date
Witness Signature	Date

Form A