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Characterization of Whole-Body Vibration Exposures in Forklift Operators

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Abstract

Characterization of Whole-Body Vibration Exposures in Forklift Operators

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Prolonged and/or frequent exposures to whole-body vibration (WBV) are known factors for musculoskeletal disorders. Although forklift operators are heavily exposed to WBV, there is still a lack of studies that systematically evaluate different interventions for mitigating WBV exposures. The present dissertation objectives were: 1) to characterize forklift operators' exposure to WBV, and 2) to evaluate the effects of three different potential interventions (i.e., forklift vibration damping systems, tire selection, and driver seat suspensions) in reducing the forklift operators' exposures to WBV. To achieve these objectives, three field-based studies were conducted with professional forklift operators to measure and analyze WBV exposures per International Organization for Standardization (ISO) 2631-1 WBV standards, and self-reported musculoskeletal pain during half of the regular shifts (approximately 4 hours). The results of the first study showed that the operators of the forklift with the mast-based vibration damping system

experienced lower WBV exposures and lower self-reported musculoskeletal pain compared to the other forklift operators without the mast-based vibration damping system. A second study found that the operators of the forklifts equipped with solid-tires experienced lower WBV exposures and lower self-reported pain than the operators of the forklifts equipped with pneumatic-tires. These results followed a dose-response relationship in those lower WBV exposures corresponded to lower self-reported musculoskeletal pain levels. Lastly, a third study revealed that the seat suspension of the forklift driver seat attenuated the majority (approximately 46 %) of the forklift's floor-measured vibration; however, the amount of vibration attenuated by either the seat suspension and/or the seat cushion vibration was weight dependent.

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DEDICATION

To my savior Lord Jesus Christ

To my loving family

Dr. Esther Meehae Joh

Ezra Jongwoo Ryou

Also, to the parents

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Chapter 1. INTRODUCTION

1.1 BACKGROUND & SIGNIFICANCE

Low back pain (LBP) is a major cause of disability that leads to activity limitations for both daily life and the work environment. (Bernard et al., 1997; Marras et al. 2007). An estimated 37% of the LBP cases worldwide are related to occupational risk factors, which corresponds to an estimated annual loss over 800,000 disability-adjusted life years (Lahiri, Markkanen, & Levenstein, 2005). Moreover, the majority of low back injuries are considered a chronic health outcome, as the symptoms and pain associated with LBP slowly develop and require long term management (Deyo, Mirza, Turner, & Martin, 2009). As such, the medical and workers' compensation costs associated with low back injuries are disproportionately higher compared to other non-fatal occupational injuries (Howard & Adams, 2018), the burden associated with back injuries can have a substantial economic impact on various stakeholders, including employers, injured workers, and their families (Bigos et al., 1986).

A high rate of low back injuries among professional vehicle operators has been previously documented (Bovenzi et al., 2006; Frymoyer et al., 1980; Magnusson, Pope, Wilder, Areskoug, & King, 1996). Previous studies have shown that LBP prevalence among professional drivers ranges from 40 to 80%, which is significantly higher than other occupations (Bovenzi, 2009). Such a high prevalence of LBP can be explained by various risk factors associated with professional vehicle operation, such as prolonged sitting, physical work demands, stress, and exposure to whole-body vibration (WBV) (Magnusson et al., 1996; Tiemessen, Hulshof, & Frings-Dresen, 2007). Several research studies have demonstrated an exposure-response relationship between WBV and the development of LBP among professional vehicle operators. Schwarze et al. (1998) found that

about 30% of 388 professional vehicle operators' (operators of forklifts, trucks, and heavy machinery) LBP was linked to WBV exposures. Bovenzi and Hulshof (1998) identified that there was an increased risk of LBP from exposure to WBV using both cross-sectional (pooled prevalence odds ratio 1.5; 95% CI 0.9-2.4) and cohort studies (age-adjusted incidence density ratio 1.8; 95% CI 1.1-3.1) by reviewing 37 studies related to professional vehicle operator's WBV exposures. Bovenzi et al. (2006) demonstrated that about 29% of the professional vehicle operators who participated in their study experienced average WBV exposures higher than the European Union (E.U.) daily vibration action limit, which refers to increased risk to an adverse health effect, including the development of LBP. Hoy et al. (2005) found a higher prevalence of LBP among forklift operators compared to non-forklift operating workers, with the odds ratio for LBP associated with WBV exposed forklift operation was 3.52.

1.2 WHOLE BODY VIBRATION MEASUREMENT

WBV, in the context of this dissertation, refers to oscillatory movements generated by workplace machines and vehicles that are transmitted into the human body (Griffin et al., 2006). When operating vehicles, vibration is often transmitted through the vehicle seats to the vehicle operators (Zucco & Gomes, 2009) and impacts several organs and structures in the operator's body. As various factors, such as road surface, vehicle speeds, and driving style, influence WBV exposures, it is crucial to assess the exposures across the diverse operating conditions (Griffin et al., 2006).

The magnitude (amount) of the WBV exposures or "acceleration," contains vibration energy content that spans a wide range of frequencies and is typically measured using an accelerometer. An accelerometer is a device that collects and converts mechanical energy into electrical output proportional to the acceleration. This measurement is collected at the point where

the WBV is considered to enter the body, such as the driver's seat (Griffin et al., 2006). In order to accommodate the wide range of frequencies and adequately capture the highest and lowest signals of the vibration, the ISO 8041-1 vibration standard recommends recording the vibration signal frequency of approximately nine times the highest frequency of interest (International Organization for Standardization, 2017). Also, it is recommended that the measurement of WBV exposures should last at least 20 minutes for vibration exposures and tasks with low variability, and at least 2 hours or more for more variable measurement conditions, to produce representative WBV exposures values (Griffin et al., 2006).

Per the ISO 2631-1 WBV standard, the frequency range of interest for the human health impact of WBV exposures is 0.5 Hz to 80 Hz (International Organization for Standardization, 1997a). Specifically, z-axis vertical WBV exposures in the range of 6–12 Hz is given greater importance. The WBV exposures in this range are known resonance frequencies of the human body, which amplifies the effects of WBV on the internal tissues, organs, and spine (International Organization for Standardization, 1997b; Zucco & Gomes, 2009).

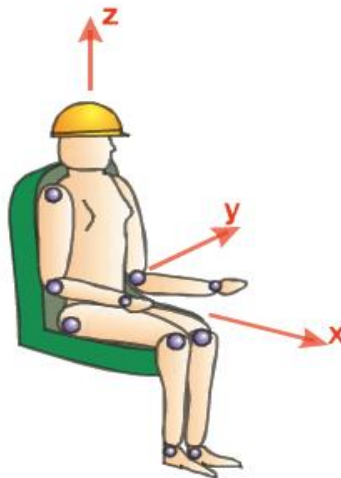


Figure 1.1. Three primary axes of the Human Body (Griffin et al., 2006)

Exposure to WBV can be assessed using the displacement of the seated body measured along three primary axes: X (front to back), Y (side to side), and Z (up and down) (Figure 1.1.)

(International Organization for Standardization, 1997b). Measuring in all three axes allows the vehicle operator's WBV exposures to be capturing for all three dimensions, such as WBV generated by accelerating and braking of the vehicle (x-axis, front and back), vehicle translation (y-axis, side to side), and vertical terrain motion (z-axis, up and down). To account for the different risks associated with the axis and the frequency of the WBV exposures, two different frequency-weightings are applied to the collected WBV exposures data: W_d weighting for x and y axes, and W_k weighting for the z-axis. Also, to account for the potential health effects associated with the WBV exposures, additional multiplying factors (k) are applied to the frequency weighted values: $k = 1.4$ for the x and y axes and 1 for the z-axis (Griffin et al., 2006; International Organization for Standardization, 1997a).

The WBV exposures are generally expressed as the root mean square (RMS) values that are weighted according to the ISO 2631-1 (1997). Following the ISO 2631-1 WBV standards, the measured WBV exposure data are converted to two parameters:

- RMS weighted average acceleration (A_w) in m/s^2 represents the average of occasional shocks and transient vibration experienced over the period of exposures (Equation 1.1).
- Vibration Dose Value (VDV) in $m/s^{1.75}$ represents the cumulative measure that is more sensitive to impulsive events that occurred during the exposures period (Equation 1.2). Impulsive vibrations are typically generated by driving over rough road surfaces, instant shock, or jolts.

Root mean square (RMS) weighted average acceleration:

$$A_w = \left[\frac{1}{T} \int_0^T a_w^2(t) dt \right]^{\frac{1}{2}} \quad (1.1)$$

Vibration Dose Value:

$$VDV = \left[\int_0^T \{a_w^4(t)\} dt \right]^{\frac{1}{4}} \quad (1.2)$$

where

$a_w(t)$: instantaneous frequency-weighted acceleration at time t ,

T : the duration of the measurement, in seconds

To evaluate occupational WBV exposures and to enable a fair comparison across different conditions or occupations, A_w and VDV parameters are often normalized to reflect 8 hours of occupational WBV exposures, as described below:

8-hour daily equivalent A_w :

$$A(8) = A_w * \left[\frac{\text{measurement duration (seconds)}}{8 \text{ hours} * 60 \text{ minutes} * 60 \text{ seconds}} \right]^{\frac{1}{2}} \quad (1.3)$$

8-hour daily equivalent VDV:

$$VDV(8) = VDV * \left[\frac{\text{measurement duration (seconds)}}{8 \text{ hours} * 60 \text{ minutes} * 60 \text{ seconds}} \right]^{\frac{1}{4}} \quad (1.4)$$

In order to evaluate the health impact, the WBV exposures parameter can be compared to the vibration threshold values recommended by various organizations. While the United States does not have any regulations for WBV exposures, the American Conference of Governmental Industrial Hygiene (ACGIH) and the International Organization for Standardization (ISO) provides voluntary guidelines and recommended thresholds (ACGIH Threshold Limit Values; ISO Action and Exposure Limit Values). The European Union (E.U.) published a directive (E.U. Vibration Directive 2002/44/EC), which was adapted from the health caution guidance thresholds from the ISO 2631-1 standard, and required all employers of workers exposed to WBV exposures to comply with the regulations assessing vibration exposure levels (E.U. Directive Provisions, 2002). This standard attempts to ensure the health of the workers by limiting the WBV exposures they experience to what are believed to be reasonable levels. According to the E.U. Directive, the

daily vibration action limits for the 8-hour average vibration [A(8)] and vibration does value [VDV(8)] are 0.5 m/s^2 and $9.1 \text{ m/s}^{1.75}$, respectively. The exposure values above these limits increase the equipment operator's chances of adverse health outcomes. When the A(8) and VDV(8) exceed the exposure limits of 1.15 m/s^2 and $21 \text{ m/s}^{1.75}$, respectively, immediate actions, including engineering controls and/or administrative controls are recommended to reduce the WBV exposures (Griffin et al., 2006).

1.3 HEALTH IMPACTS OF WHOLE-BODY VIBRATION

WBV may cause various symptoms such as discomfort, pain, vomiting, motion sickness, and paresthesia (Uchikune, 2004). Continuous exposure to WBV over a prolonged duration may further exacerbate these symptoms and affect various physiological structures and systems of the body, including musculoskeletal, cardiovascular, cardiopulmonary, metabolic, endocrinologic, nervous and gastrointestinal systems (Thalheimer, 1996). Hood et al. (1966) identified that an increase of arterial blood pressure, heart rate, cardiac output, oxygen consumption, and ventilation volume occurred in adults after being exposed to sinusoidal vibrations. Duffner et al. (1962) reported that 4-minute exposure to vertical low-frequency WBV caused breathing rate decrease and oxygen consumption increase, which can lead to vibration-induced hyperventilation.

Among the aforementioned adverse health effects, LBP is consistently associated with WBV exposures more so than other health outcomes; therefore, WBV is considered a leading risk factor for LBP among professional vehicle operators (Bovenzi, 2005, 2010). WBV may affect LBP through different mechanisms. Prolonged exposure to WBV compresses the intervertebral discs and causes them to displace from the spine (Bongers, Boshuizen, Hulshof, & Koemeester, 1988). Also, WBV exposures cause muscle fatigue by improper transportation of nutrients, excretory products, and other metabolites in and out of the cells in surrounding tissues of the spine (Grenier,

Eger, & Dickey, 2010; Magnusson et al., 1996). In addition, to WBV exposures, prolonged seating, and operating with awkward postures may increase the risk of disc protrusion among professional vehicle operators (Bovenzi, 1996).

Exposure to WBV has also been identified as a factor in decreasing day-time alertness and vigilance among professional vehicle operators. Du et al. (2017) indicated that the correlation between response time and WBV exposures were shown where the reaction time decreased when the WBV exposures decreased. A study by Kelly et al. (2011) concluded that patients with chronic LBP experience relatively higher sleep disturbance compared to the control group, which leads to poor day-time function. The decrease of vigilance and sleep quality due to the WBV exposures may impact the driving performance among the professional vehicle operators and lead to secondary or tertiary injuries or vehicle-related accidents (Conway, Szalma, & Hancock, 2007).

1.4 WHOLE-BODY VIBRATION IN FORKLIFT OPERATION AND PRIOR STUDIES

Forklifts are among the most heavily utilized industrial vehicles due to their flexibility and ability to transport various materials that differ in size and weight. Over 1 million forklifts were sold by 20 largest manufacturers worldwide, with the annual revenues of \$31.45 billion (Gajšek, Đukić, & Opetuk, 2015). In 2015, about 226,000 forklifts were sold in the U.S., which represents about 5% increase compared to 2006, the highest sales before the 2008 economic recession ("Forklift Sales Hit Record in 2015," 2016). Material moving operators in Washington State, including forklift drivers, constitute about 5% of the transportation and material handling workforce (U.S. Bureau of Labor Statistics, 2019).

Despite being a relatively small segment of the transportation sector, in the United States, around 35,000 workers are injured annually due to forklift-related accidents, including approximately 100 deaths (OSHA, 2018). Moreover, forklift operators experience high levels of

WBV exposures, especially with impulsive shock exposures, when performing material transportation (Hoy et al., 2005; Waters et al., 2007). With the extensive amount of WBV exposures experienced by the operators, and the combination of prolonged sitting and awkward postures, forklift operators are exposed to significant risk factors for LBP development. Zucco and Gomes (2009) stated that about 87% of the WBV exposures measured in the forklifts exceeded the ISO 2631-1 standard action limit. Viruet et al. (2008) identified that the relative risk for LBP among the forklift operators was more than two times higher compared to other workers.

WBV exposures are affected by various factors including cab suspension, seat suspension, tire types, operator characteristics (e.g., body mass), postures, and driving speed and behavior (Blood, Ploger, & Johnson, 2010; Kumar, 2004; Lemerle & Mistrot, 2001; Malchaire, Piette, & Mullier, 1996; Ozkaya et al., 1994; Rehn, Lundström, Nilsson, Liljelind, & Järholm, 2005). Some studies have evaluated some of these factors (i.e., tires and driver seats) as control measures to reduce the forklift operators' exposure to WBV (Blood et al., 2010; Malchaire et al., 1996; Motmans, 2012). Previous studies found that inflated pneumatic-tires (tires with a rubber casing enclosing an air-filled chamber) had lower WBV exposures compared to solid-tires (tires made with solid rubber without an inflatable inner tube) in forklift operation (Joubert, 2002b; Malchaire et al., 1996; Zucco & Gomes, 2009). In addition, the magnitude of the vibration is highly influenced by the stiffness of the tire and the amount of tire pressure (for pneumatic-tire) (Lemerle & Mistrot, 2001; Sherwin, Owende, Kanali, Lyons, & Ward, 2004; Verschoore, Pieters, & Pollet, 2003). Blood et al. (2010) demonstrated that both mechanical and air-suspension seats significantly reduce floor-measured vibration during forklift operation while an air-suspension seat had superior vibration attenuation performance than a mechanical suspension. Malchaire et al.

(1996) also found that a mechanical suspension was shown to be more effective in reducing WBV compared to a static (i.e., suspension-less) seat in various forklift operation conditions.

Unlike automobiles, buses, and light-, medium-, and heavy-duty trucks, forklift suspensions are purposely designed to provide minimal damping for load stability when heavy loads are being transported (Jönsson, 2005). Most forklifts only rely on elastomeric mounts (i.e., rubber bearing) to isolate vibration generated from drivetrains being transmitted to the chassis of the forklifts (CLARK Europe GmbH, 2010; Fujian Southchina Heavy Machinery Manufacture Co., 2020; Hyster Company, 2019; Linde Material Handling, n.d.). However, hydraulic pistons that are directly connected between the mast and cabin of the forklift have been introduced to further reduce vibration exposures during loading and unloading in some forklifts (Linde Material Handling, n.d.). But, the effectiveness of these vibration damping systems in the forklifts in reducing WBV has not been systematically evaluated.

Different forklift tire types can be one of the ways to mitigate WBV exposures. Forklift trucks are typically equipped with one of two types of tires: solid-tires—tires made with solid rubber without an inflatable inner tube, and pneumatic air-filled tires—tires with a rubber casing enclosing an air-filled chamber. In general, most forklifts in the U.S. are equipped with solid-tires to minimize the risk of puncture, high maintenance costs, and lost operating time due to the surface conditions in many rugged industrial environments (Joubert, 2002a). Tire selection can have an influence on vibration exposure, as vibration energy travels through the tires before entering the forklift body structure and is transmitted to the forklift operators.

A seat with superior vibration attenuation properties has been considered a reliable and cost-efficient method for reducing forklift operator WBV exposures (Ahmadian, Seigler, Clapper, & Sprouse, 2002; Blood, Yost, Camp, & Ching, 2015; Ning et al., 2016). A wide array of seats

with various types of seat suspensions are available for most commercially-operated forklifts. A mechanical suspension seat (industry standard) is structurally less complicated and more economical due to its structural simplicity as compared to passive air-suspension and active suspension seats that require compressed air and electric power.

1.5 RESEARCH GAPS

Despite forklifts being equipped with different types of vibration damping systems, the effectiveness of these damping systems on reducing WBV exposures are not well recognized nor have been sufficiently evaluated for WBV mitigation. Although previous studies have compared the WBV exposures between different types and models of forklifts, these studies have not systematically described whether the structures or features in each forklift contributed to altering WBV exposures. Deshmukh (2009) characterized and compared seven different forklift models with varying load capacity, and engine types used at both indoors and outdoors at an aircraft manufacturing site. Joubert (2002b) compared the WBV exposures of nine different forklifts, which differed in capacity, brands, and engine type. Despite the significant difference of WBV exposures between the operating conditions, the findings of these studies were limited to determining whether any of the forklift features or structural differences contributed toward reducing WBV exposures.

Many of the previous studies evaluating the WBV exposures of different forklift tire types under prescribed, controlled operating conditions may not be generalized to realistic occupational settings the forklift operators face during their regular work. Malchaire et al. (1996) and Zucco & Gomes (2009) compared the WBV exposures of forklifts with different tire types (pneumatic vs. solid tires) and demonstrated that forklift tires could significantly affect WBV exposures. However, these studies were conducted under very specific and controlled operating conditions

and may not represent actual operating conditions where forklifts are operated under various and diverse operating conditions, such as different road surfaces, operating speeds, and load sizes. Therefore, there is a critical need to more systematically evaluate the effects of different tire types on WBV exposures in realistic environments (i.e., during forklift operators' actual work shift).

Forklift seat suspension performance has been extensively evaluated, but the combined role of the seat foam and seat suspension in altering forklift operator WBV exposures has not been investigated. The methods used in the previous studies evaluating the WBV mitigation properties of different driver seats (i.e., no-suspension, mechanical, and air-suspension) have not broken down seat suspension performance to understand the relative contribution of the seat suspension and seat cushion in attenuating the WBV exposures (Blood et al., 2010; Malchaire et al., 1996; Motmans, 2012). With the current methods, it is not known how much vibration mitigation comes from the seat cushion, how much mitigation comes from the seat suspension, and whether the seat suspension and cushion work in tandem to reduce the WBV exposures, or if they interact and interfere with one another when mitigating the WBV. The performance of the driver seat on attenuating WBV was mainly determined by the seat suspension spring stiffness and damping coefficient (Ning et al., 2016). Also, the operators' weight profoundly influences the performance of the seat (Boileau & Rakheja, 1990; Chen et al., 2003; Malchaire et al., 1996). Therefore, it is important to understand the influence that the seat suspension and seat cushion have altering vibration exposure by the driver.

1.6 RESEARCH OBJECTIVES, SPECIFIC AIMS, IMPACT

The primary objectives of this dissertation were: 1) to characterize forklift operators' exposure to WBV during their actual work in a manufacturing site and 2) evaluate the effects of three different potential intervention measures (i.e., mast vibration dampening system, tire, and

seat suspension) in reducing the forklift operators' exposure to WBV. The ultimate goal of this study was to evaluate and compare various vibration mitigating strategies that may be of benefit to the forklift operators and reduce WBV exposures. These study objectives were investigated through the following three Specific Aims:

Specific Aim 1

Chapter 2 of the dissertation describes a study to characterize and compare the WBV exposures between two different types of commonly-used forklift trucks with and without the mast-based vibration damping system.

Hypothesis 1: WBV exposures experienced by the forklift operators operating the forklifts with and without the mast-based vibration damping system will be different.

Specific Aim 2

Chapter 3 of the dissertation aims to characterize the WBV exposures of forklift operators using the current standard air-filled pneumatic- and solid- tires, and determine whether WBV exposures differences exist between the two forklift tire groups (pneumatic- vs. solid-tire) during their actual work.

Hypothesis 2: WBV exposures experienced by the forklift operators operating forklifts with pneumatic- and solid-tires will be different.

Specific Aim 3

Chapter 4 of the dissertation characterizes the WBV exposure mitigation properties of a mechanical forklift driver seat and determines how the seat suspension and seat cushion alter the WBV exposures.

Hypothesis 3: The amount of WBV exposures attenuated by the seat suspension and seat cushion will be different.

Concluding Chapter

Chapter 5 summarizes the overall findings of the studies with respect to each of the specific aims. It also summarizes the potential impact of the research on the health outcomes of forklift operators. The chapter briefly examines possible solutions among three intervention sources (i.e., mast vibration damping system, tire, and seat) to reduce overall WBV exposures to forklift operators. It also describes the potential for companies and employers to more efficiently operate their current forklifts and identify ways to mitigate their operators' WBV exposures with their current equipment. How this work may ultimately reduce work-related injuries associated with forklift operation and the costs related to those injuries is discussed. Finally, the implications of this research on future research are presented.

Chapter 2. DIFFERENCES IN WHOLE-BODY VIBRATION EXPOSURES BETWEEN FORKLIFTS WITH AND WITHOUT MAST-BASED VIBRATION DAMPING SYSTEM

2.1 INTRODUCTION

Professional vehicle operators—including forklift operators—constitute one of the most vulnerable groups for work-related low back pain (LBP) (Massimo Bovenzi et al., 2006; Magnusson et al., 1996). Among various risk factors (awkward postures, prolonged sitting, and exposures to whole-body vibration), whole-body vibration (WBV) has been consistently associated with LBP (Bovenzi & Hulshof, 1998; Bovenzi et al., 2006; Schwarze et al., 1998; Wegscheider, 2014). Previous studies have shown that forklift operators are exposed to high levels of WBV with frequent impulsive shock exposures (Hoy et al., 2005; Waters et al., 2007).

The high WBV exposures in the forklift trucks are partly due to the fact that forklifts' suspension has a much more limited amount of travel (i.e., displacement) compared to other vehicles' suspensions (e.g., passenger cars and trucks). As discussed in Chapter 1, this limited chassis suspension displacement promotes lateral load stabilization while compromising its ability to reduce a driver's exposure to WBV. Such high WBV exposures may explain previous study findings that the relative risk for developing LBP for the forklift operators was more than twice that of other workers (Viruet et al., 2008; Waters, Genaidy, Viruet, & Makola, 2008).

Due to forklift trucks having limited suspension travel, previous studies have mainly focused on seat suspension and tires as potential intervention measures. A study by Malchaire et al. (1996) showed that pneumatic tires, a tire with a rubber casing enclosing an air-filled chamber, provided a better performance of reducing forklift WBV exposures compared to solid tires, a tire

made with solid rubber without an inflatable inner tube. Motmans (2012) and Blood et al. (2010) studies showed that air suspension seats were more effective in reducing WBV exposures as compared to mechanical suspension seats. In addition, other studies have identified important factors affecting WBV exposures in various forklifts. Deshmukh (2009) stated that higher WBV exposures were observed with the forklifts operated outdoor compared to indoor environments. Joubert (2002) stated that the condition of forklifts (with regard to maintenance and upkeep) was also an important factor affecting WBV exposures.



Figure 2.1. Front Axle mounted on the mast (left) and a hydraulic shaft connected between mast and cabin of the forklift (right) (Linde Material Handling, n.d.).

Although it was described in the previous studies that the structure of forklift, including vibration damping systems, may have a significant influence on the WBV exposures, no studies have been conducted to evaluate how or whether these suspension structures mitigate WBV exposures. Therefore, the main objective of this study was to characterize and compare the forklift operators' WBV exposures when operating the forklifts equipped with and without a mast-based vibration damping system. *It was hypothesized that the WBV exposures experienced by the forklift operators operating the forklifts with and without the mast-based vibration damping system would be different.* If there are differences in the WBV exposures between the two types of forklifts, then

purchasers of forklifts can choose to procure forklifts, which lower WBV exposures. The forklift manufacturers can also use this result to improve the vibration mitigation of their forklift designs.

2.2 METHODS

2.2.1 *Subjects*

With support from the site managers and using flyer solicitation, ten professional forklift operators (9 males and 1 female) in a manufacturing facility were recruited to participate in this field-based study. All subjects were informed about the study's aim, procedures, and possible risks and benefits. Once the subjects were fully briefed about the study, each subject gave informed consent prior to participation in the study.

2.2.2 *Forklifts*

The study evaluated two types of forklifts with (Forklift A) and without (Forklift B) a mast-based vibration mitigating system (Figure 2.2). Otherwise, the two forklifts were comparable in load capacity, engine, tire, and seat suspension, as shown in Table 2.1.

Table 2.1. Forklift specifications

		Forklift A	Forklift B
Brand		H50 (Linde Material Handling, Aschaffenburg, Germany)	H100 (Hyster-Yale, Cleveland, OH)
Load Capacity		5 tons	
Engine		Volkswagen 3.6L LPG Engine	Kubota 3.8L LPG Engine
Tires (number of tires in each axle)	Front axle (4)	XZM 8.25R15 Pneumatic Tires (Michelin tire, Clermont-Ferrand, France)	
	Rear axle (2)	XZM 225/75R Pneumatic Tires (Michelin tire, Clermont-Ferrand, France)	
Driver Seat (Mechanical Suspension)		MSG-65 (Grammer AG, Amberg, Germany)	FLM 1815 (Sears Seating, Davenport, IA)



Figure 2.2. Forklifts tested: Forklift A with mast-based vibration damping system (left) and Forklift B without the mast-based vibration damping system (right)

The subjects were divided into two groups of operators based on the forklift they regularly operated. To determine homogeneity between the two groups, relevant demographic and work history data were collected (Appendix A) and statistically compared using the Wilcoxon signed-rank tests. As shown in Table 2.2, no significant differences were found in the demographics and work history between the two groups.

Table 2.2. Subjects' demographic information [Median (25th, 75th percentile)] of the two experimental groups. *p*-values were obtained from the Wilcoxon signed-rank tests.

	Forklift A (n=5)	Forklift B (n=5)	<i>p</i> -value
	Median (25 th , 75 th)	Median (25 th , 75 th)	
Age (years)	54.0 (35.5, 65.0)	51.0 (34.5, 57.0)	0.62
Operating Experience (years)	29.2 (9.1, 36.3)	22.0 (6.6, 29.6)	0.60
Weight (kg)	97.5 (81.9, 101.6)	107.3 (87.7, 122.5)	0.22
Height (cm)	177.8 (167.6, 184.2)	185.4 (183.5, 185.4)	0.09
BMI	30.1 (26.4, 33.6)	31.6 (25.5, 35.8)	0.90

2.2.3 Whole-Body Vibration Data Collection

Among the five subjects in each forklift operator group, three subjects repeated the measurements using the same model, but a different forklift than their first measurement. As each of the three subjects repeated a measurement with different forklifts, eight unique forklift/driver combinations were collected from each forklift group. For WBV, raw unweighted acceleration data were collected at a sampling rate of 1,280 Hz using a data recorder (DA-40; Rion Co. LTD, Tokyo, Japan) and two accelerometers per ISO 2631-1 WBV standard. A seat-pad tri-axial accelerometer (Model 352B41; PCB Piezotronics, Depew, NY) was mounted on the driver's seat top; an additional single-axial accelerometer (Model 352C33; PCB Piezotronics, Depew, NY) was magnetically mounted on the floor of the forklift cabin. Concurrently, a portable global positioning system (GPS) unit (Model CR-Q1100P; Qstarz Co., Taipei, Taiwan) was mounted on the forklift dashboard to collect forklift speed and location data at 1 Hz (Figure 2.3.). The subjects were asked to operate their forklifts in the same manner as they would typically do during their regular work shift.

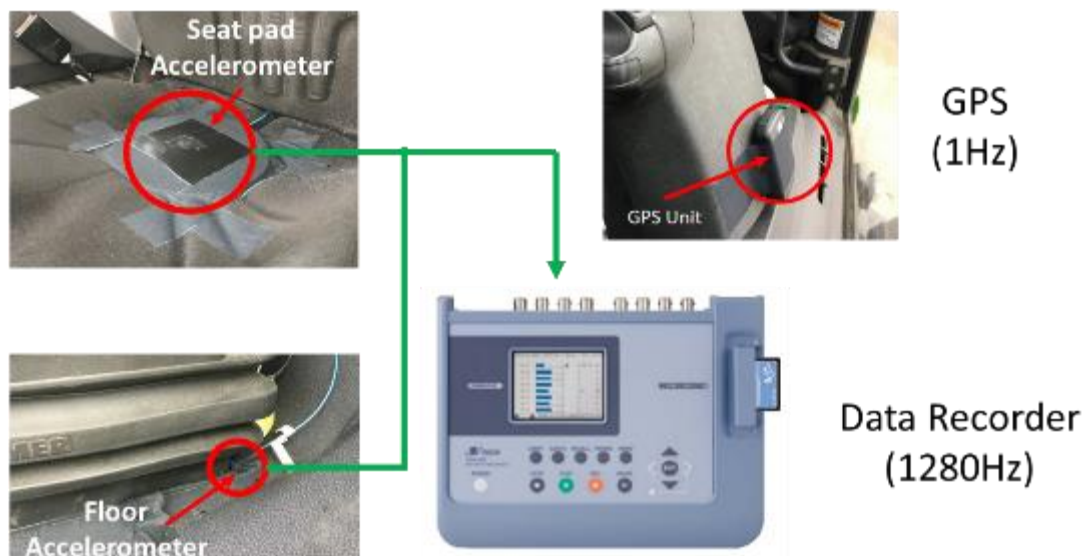


Figure 2.3. Whole-Body Vibration measurement instrumentation

2.2.4 Whole-Body Vibration Data Processing

Regular Work Shift Data Processing

Referring to the previously described methods (Blood et al., 2011), the collected raw acceleration data was aligned with the GPS data and combined into one file, using a LabVIEW program (Version 2018; National Instruments, Austin, TX), to analyze vibration data by forklift speed and location. The combined raw acceleration data file was weighted with the ISO vibration weightings to calculate weighted average acceleration (A_w) and vibration dose values (VDV) as described in ISO 2631-1 (1997). A_w and VDV were normalized to daily equivalent vibration exposure measures: $A(8)$ and $VDV(8)$, in order to draw health implications by comparing to the European Union (EU) Directives (EU Directive Provisions, 2002) daily exposure action limit [$A(8) = 0.5 \text{ m/s}^2$; $VDV(8) = 9.1 \text{ m/s}^{1.75}$].

Also, the amount of time the forklifts could be operated before reaching the EU daily action limits for $A(8)$ and $VDV(8)$ were calculated using the following equations:

Time to Action Limit (TAL) for $A(8)$:

$$TAL(A[8]) = \left(\frac{0.5}{A(8) \text{ exposure value}} \right)^2 * 8 \quad (2.1)$$

Time to Action Limit (TAL) for $VDV(8)$:

$$TAL(VDV[8]) = \left(\frac{9.1}{VDV(8) \text{ exposure value}} \right)^4 * 8 \quad (2.2)$$

Using the Equation 2.3., the Seat Effective Amplitude Transmissibility (SEAT) value was calculated and compared between two forklift types to determine the performance of the driver seats in attenuating the floor-measured vibration. The SEAT value represents the ratio of WBV

exposures the forklift operators experienced relative to the amount of floor-measured vibration exposures

Seat Effective Amplitude Transmissibility (SEAT):

$$SEAT (\%) = \frac{\text{seat measured WBV exposure value}}{\text{floor measured WBV exposure value}} * 100 \quad (2.3)$$

As WBV was collected during subjects' regular work-shifts, some operational factors, which affects WBV exposures, may have differed between the forklift groups, including routes, duration, and operating speed. To determine potential differences in these operational factors between the two groups, the median speed (km/h), operating duration (min), and proportion of operating time over the measurement duration (%) were calculated based on the GPS data and compared between the two groups (Table 2.3.). The operating time was identified when the forklift speed was greater than 1 km/h, or the GPS coordinates changed within 60 seconds.

Common Terrain (route) Comparison

To compare the WBV exposures between the two forklift groups under the similar operating conditions, the GPS coordinates were used to identify the common 230-meter long route segment over which both forklift types traveled during the regular shift (Figure 2.4., yellow route). The WBV data from this common route were processed and analyzed, as described in the section above.



Figure 2.4. A map showing GPS coordinates of forklift operating routes (pink) and the selected common route (yellow)

Analyzed Data Types

Based on the WBV exposures data processing, 8-hour normalized WBV exposures of each forklift type were compared using the following three types of data: (1) WBV exposures during the operator's regular work which involved both activity (forklift movement) and inactivity (the forklift being idle or stationary); (2) WBV exposures solely based on when the forklifts were moving (active), to account for potential differences in duty cycles between forklifts (activity and inactivity); and (3) WBV exposure during operation over the common route.

2.2.5 *Power Spectral Density and Transmissibility Analysis*

Power Spectral Densities (PSDs) from the 230-meter common route data were calculated as the measure of vibration's power content by frequency ($\text{m}^2/\text{s}^3/\text{Hz}$). A custom-built LabVIEW program (Version 2018; National Instruments, Austin, TX) was used to extract and summarize the vibration energy content relative to the frequency range of 0 to 18 Hz with a frequency resolution of 0.5 Hz. This frequency range was selected to accommodate the dominant vibration-transmitting frequency range of the forklift below 20 Hz (Viruet et al., 2008). PSDs were compared between the two forklifts to identify the dominant frequencies of the forklift specific vibration. In addition, the energy transmissibility of the vibrations in a frequency domain was evaluated to determine the driver seat's vibration attenuation performance by frequency. The transmissibility represents the ratio of the PSDs measured at the seat and floor. A value greater than 1 indicates the amplification of the floor-measured vibration at the seat, while a value less than 1 indicates the attenuation of the floor-measured vibration at the seat.

2.2.6 *Subjective Musculoskeletal Pain*

A 10-point-scale questionnaire (Appendix B) was administered before and after the subjects operated their forklift to measure the self-reported musculoskeletal pain in eight body locations (neck, upper back, lower back, buttocks/legs, shoulder, wrist/hand, knees, and ankle/feet). The scale ranged from 0 to 10 with verbal anchors: 0 - "no pain at all," and 10 - "the worst pain you can imagine." The questionnaire was adapted from previous studies that evaluated musculoskeletal discomfort among professional drivers (Kim, Dennerlein, & Johnson, 2018; Kim et al., 2016; Kim, Zigman, Dennerlein, & Johnson, 2018).

2.2.7 *Statistical Analysis*

The independent and dependent variables of the current study are as follows:

- Independent variables:
 - Forklift: with and without the mast-based vibration damping system
- Dependent variables:
 - WBV exposures parameters [A(8) and VDV(8)] from the whole measurement duration and the common route
 - Time to action limits (TAL) from the whole measurement duration and the common route
 - Seat Effective Amplitude Transmissibility (SEAT) from the whole measurement duration and the common route
 - Power Spectral Density and Transmissibility ratio from the common route
 - Self-reported musculoskeletal pain levels in each body location experienced by the forklift operators

All the dependent variables were summarized with the median and interquartile range value (25th and 75th percentile) due to the small sample size and non-normality. Statistical analyses were performed using a statistical software program (JMP Version 15; SAS Institute; Cary, NC). Given the non-normality, the Wilcoxon signed-rank tests were used to test the hypothesis that WBV exposures parameters, TAL, and SEAT value would be different between the forklifts with and without the mast-based vibration damping system. In addition, the self-reported musculoskeletal pain levels were analyzed using Wilcoxon signed-rank test to determine whether the pain levels differed in each body location before and after forklift operation between the two forklifts. Statistical significance was noted when a p-value was less than 0.05.

2.3 RESULTS

2.3.1 *Determination of Predominant Exposure Axis and Comparability of Whole-Body Vibration Exposures between Forklifts with and without Mast-based Vibration Damping System*

The results showed that the vertical z-axis was the predominant axis of WBV exposures for both forklift types (Figure 2.5.). Per ISO 2631-1 WBV standards, the z-axis exposure measures were compared between the two forklift types.

How the forklifts were operated are compared and summarized in Table 2.3. The results indicated that the two forklifts were operated similarly; therefore, it is reasonable to compare the WBV exposures between two forklift groups.

Table 2.3. Comparison of forklift operation [median (25th, 75th)] between the forklift with (Forklift A) and without (Forklift B) the mast-based vibration damping system

		Forklift A (n=8)	Forklift B (n=8)	p-value
		Median (IQR)	Median (IQR)	
Forklift Operating Duration	Duty cycle (%)	43.1% (23.7, 56.4)	37.5% (27.9, 56.2)	1.00
	Only Moving (minute)	88.8 (57.2, 132.7)	78.4 (60.2, 105.4)	0.71
	Moving and Non-moving (minute)	281.7 (219.2, 310.5)	211.4 (176.4, 235.2)	0.05
Speed (km/h)	Only Moving	11.6 (9.4, 13.7)	11.0 (7.2, 14.3)	0.79
	Moving and Non-moving	4.4 (2.9, 6.3)	4.2 (2.9, 5.4)	0.71

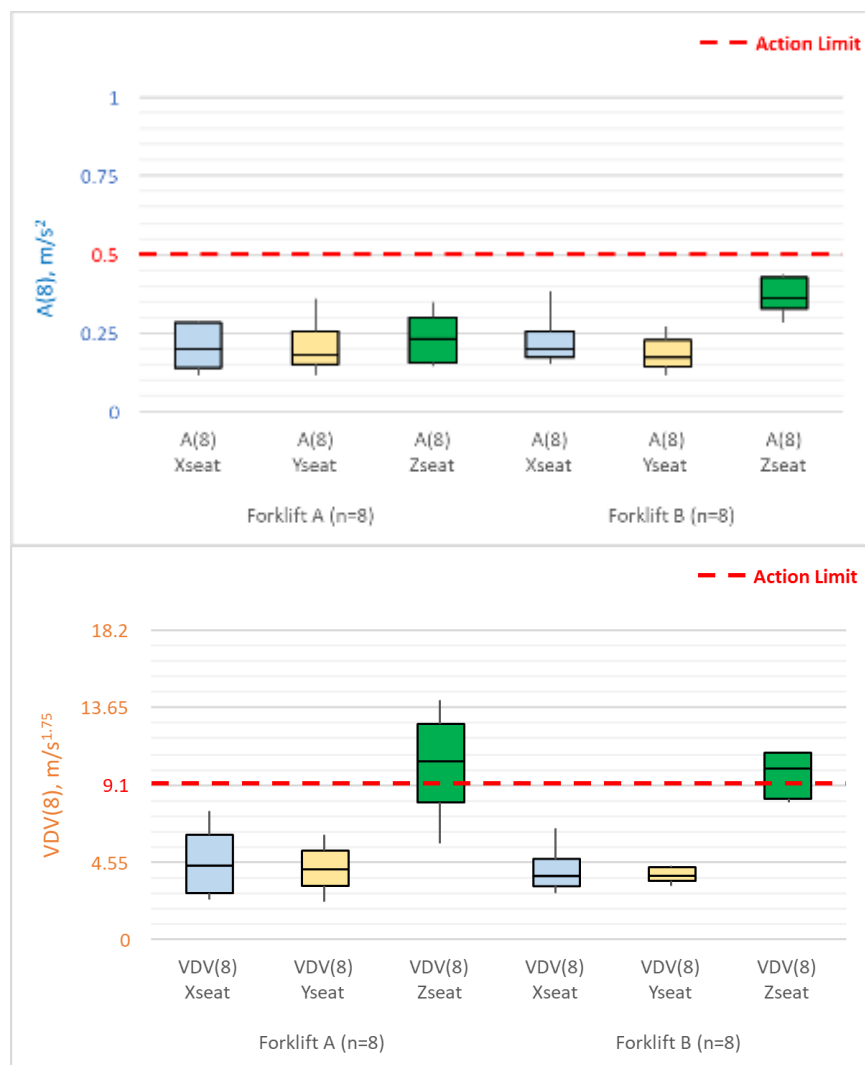


Figure 2.5. $A(8)$ and $VDV(8)$ exposures by forklift with (Forklift A) and without (Forklift B) the mast-based vibration damping system, for the fore-aft (X), lateral (Y), and vertical (Z) axis.

Exposures were expressed relative to the European Union's daily vibration action limits (red dashed line). The boxes indicate interquartile ranges; the horizontal line in the boxes are median values; whiskers indicate maximum and minimum values.

2.3.2 Comparison of Whole-Body Vibration Exposures between Forklifts with and without Mast-based Vibration Damping System During the Whole Regular Work Shift.

The floor-measured $A(8)$ and $VDV(8)$ WBV exposures during the regular work shift showed that Forklift B, the forklift without the mast-based vibration damping system, had significantly higher WBV exposures ($p = 0.03$, and $p = 0.02$, respectively) compared to Forklift A, the forklift with the mast-based vibration damping system (Figure 2.6.). Similarly, the seat-

measured A(8) WBV exposures on Forklift B were significantly higher compared to Forklift A; however, the seat-measured VDV(8) WBV exposures were not significantly different between the two forklifts ($p = 0.56$). The seat-measured A(8) WBV exposures in both forklifts did not exceed the EU action limit (0.5m/s^2), while VDV(8) WBV exposures in both forklifts were above the EU action limit ($9.1\text{ m/s}^{1.75}$).

Using the median z-axis seat-measured A(8) and VDV(8) WBV exposures, the time required to reach the action limits (TAL) for VDV(8) was not significantly different ($p = 0.56$) between the two forklifts (Figure 2.7.). The result also indicated that each forklift would take approximately 4 hours to reach the action limit ($9.1\text{ m/s}^{1.75}$). In contrast, TAL for A(8) was well above 8 hours for both forklifts, where the TAL difference between the groups was significant ($p < 0.01$).

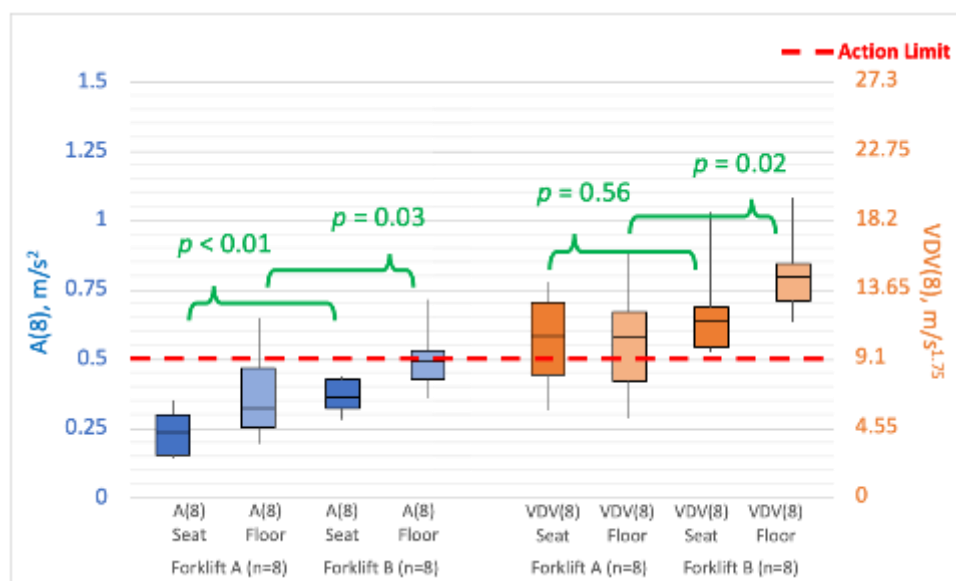


Figure 2.6. A(8) and VDV(8) WBV exposures between the forklift with (Forklift A) and without (Forklift B) the mast-based vibration damping system during the regular work shift. The red dashed line indicates the European Union's daily vibration action limits. The boxes indicate interquartile ranges; the horizontal line in the boxes are median values; whiskers indicate maximum and minimum values.

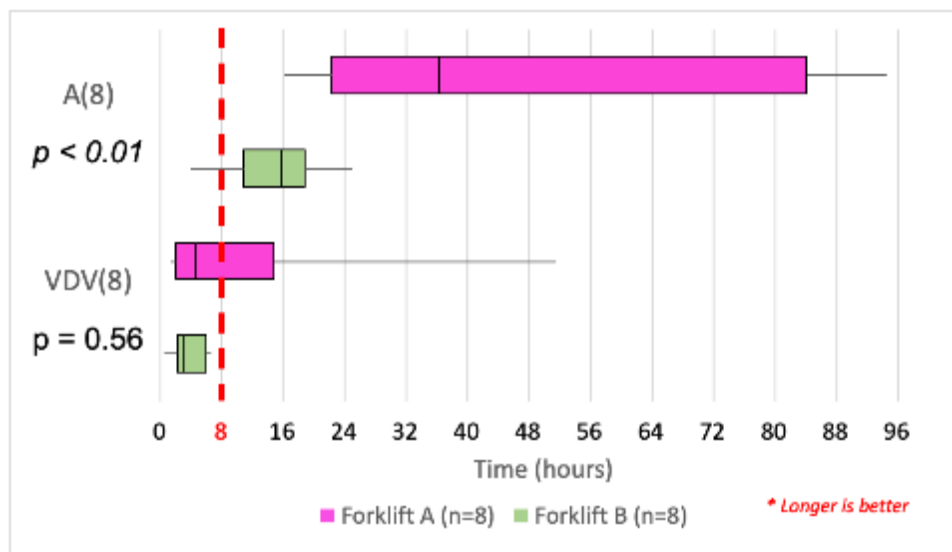


Figure 2.7. Time to action limit (TAL) based on A(8) and VDV(8) WBV exposures between the forklift with (Forklift A) and without (Forklift B) the mast-based vibration damping system based on the regular work shift exposures. The boxes indicate interquartile ranges; the horizontal line in the boxes are median values; whiskers indicate maximum and minimum values.

2.3.3 Comparison of the Whole-Body Vibration Exposures between Forklifts with and without Mast-based Vibration Damping System Based Solely on Forklift Movement/Operation During the Regular Work Shift

WBV exposures, based solely on when forklifts were in motion, were compared between the two forklifts. The result showed that Forklift B had significantly higher floor-measured A(8) and VDV(8) WBV exposures ($p < 0.04$ and $p = 0.02$, respectively), compared to Forklift A (Figure 2.8.). The seat-measured A(8) WBV exposures in Forklift B were significantly higher compared to Forklift A ($p < 0.01$). Although the seat-measured Forklift B VDV(8) WBV exposures were higher than Forklift A, the differences were not significant ($p = 0.32$). The seat-measured A(8) WBV exposures in Forklift B exceeded the E.U. action limit (0.5 m/s^2), while the seat-measured A(8) WBV exposures in Forklift A did not (Figure 2.8.). The seat-measured VDV(8) WBV exposures in both forklifts did not exceed the EU action limit ($9.1 \text{ m/s}^{1.75}$). Due to the exposures

contrast, the time to reach the action limit based on A(8) was three times longer with Forklift A compared to Forklift B (Figure 2.9.).

The A(8) Seat Effective Amplitude Transmissibility (SEAT) values showed that the driver seats in both forklifts reduced the floor-measured vibration (59-77%) (Table 2.4.). Despite the lack of statistical significance, the A(8) SEAT value in Forklift A was lower compared to Forklift B ($p = 0.13$). Conversely, the VDV(8) SEAT value was higher with Forklift A compared to Forklift B ($p = 0.05$).

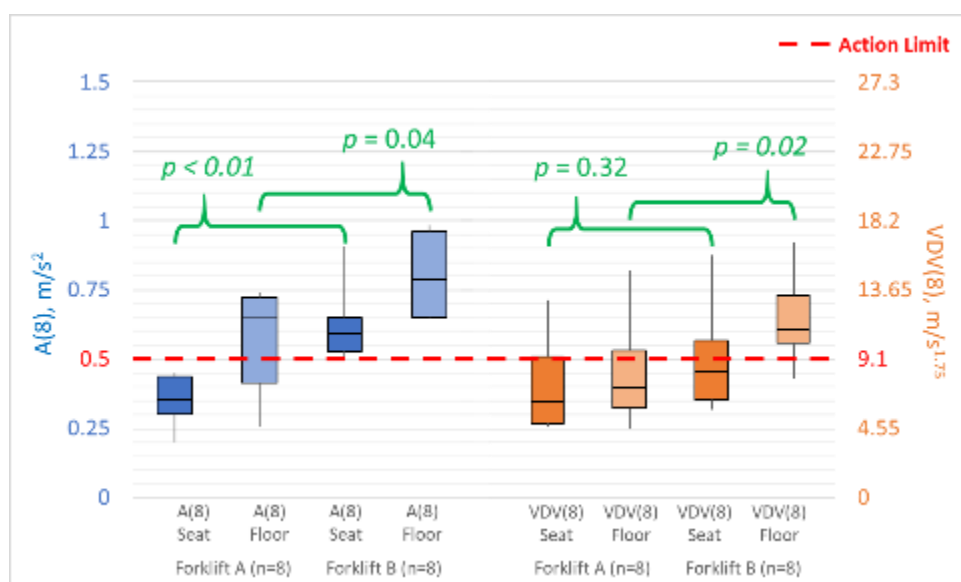


Figure 2.8. A(8) and VDV(8) WBV exposures between the forklift with (Forklift A) and without (Forklift B) the mast-based vibration damping system based solely on the periods of forklift movement/operation during the regular work shift. The red dashed line indicates the European Union's daily vibration action limits. The boxes indicate interquartile ranges; the horizontal line in the boxes are median values; whiskers indicate maximum and minimum values.

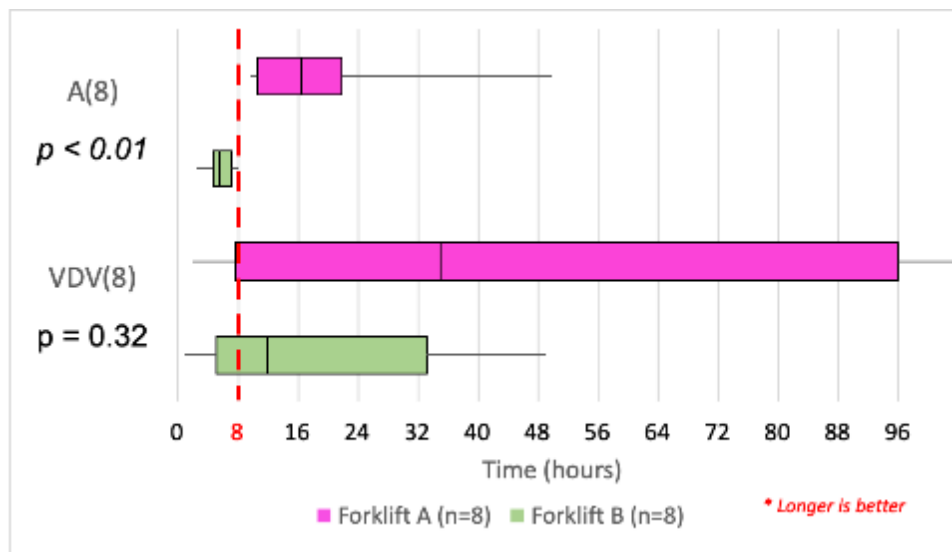


Figure 2.9. Time to action limit (TAL) based on A(8) and VDV(8) WBV exposures between the forklift with (Forklift A) and without (Forklift B) the mast-based vibration damping system based solely on the periods of forklift movement/operation during the regular work shift. The boxes indicate interquartile ranges; the horizontal line in the boxes are median values; whiskers indicate maximum and minimum values.

Table 2.4. Comparison of median (25th, 75th) regular work shift A(8) and VDV(8) Seat Effective Amplitude Transmissibility (SEAT) between the forklift with (Forklift A) and without (Forklift B) the mast-based vibration damping system based solely on the periods of forklifts movement/operation

Parameter	Forklift A (n=8)	Forklift B (n=8)	p-value
	Median (IQR)	Median (IQR)	
A(8) SEAT	58.8% (48.6, 67.7)	76.6% (60.9, 83.4)	0.13
VDV(8) SEAT	88.0% (83.9, 99.2)	75.6% (60.6, 79.3)	0.05
Speed (km/h)	11.59 (9.39, 13.67)	11.0 (7.20, 14.33)	0.79

2.3.4 Comparison of the Whole-Body Vibration Exposures between Forklifts with and without Mast-based Vibration Damping System while Operated Over the Common Route

As shown in Table 2.5, the two forklifts were operated similarly over the common route, which ensured the fair comparisons between the two forklifts when traveling over the same common terrain.

Table 2.5. Comparison of the [median (25th, 75th)] between the forklift with (Forklift A) and without (Forklift B) the mast-based vibration damping system when traversing over the common route

	Forklift A (n=8)	Forklift B (n=8)	p-value
Measurement Time (sec)	42.0 (36.0, 50.0)	41.0 (35.0, 43.8)	0.26
Avg Speed (km/h)	21.9 (17.5, 22.4)	22.3 (20.7, 22.8)	0.26

Similar to the regular work shift WBV exposure comparisons based solely on forklift operation/movement, the common route A(8) and VDV(8) WBV exposures measured at the floor of Forklift B were significantly higher compared to Forklift A (p 's < 0.01) (Figure 2.10.). The seat-measured A(8) and VDV(8) WBV exposures were also significantly higher for Forklift B than Forklift A (p 's < 0.01). The seat-measured A(8) and VDV(8) WBV exposures in Forklift B exceeded the EU daily vibration action limits, whereas Forklift A measurements were below the action limits. This exposure contrast resulted in a significantly longer time to reach action limits with Forklift A compared to Forklift B, approximately 2.5-fold for A(8) and 10-fold for VDV(8) WBV exposures differences (Figure 2.11.).

Both A(8) and VDV(8) SEAT values showed that the driver seats in both forklifts effectively attenuated floor-measured vibration (30-43%) over the common route (Table 2.6.). However, no significant difference in A(8) and VDV(8) SEAT values was found between the two forklift seats ($p = 0.51$, $p = 0.61$, respectively).

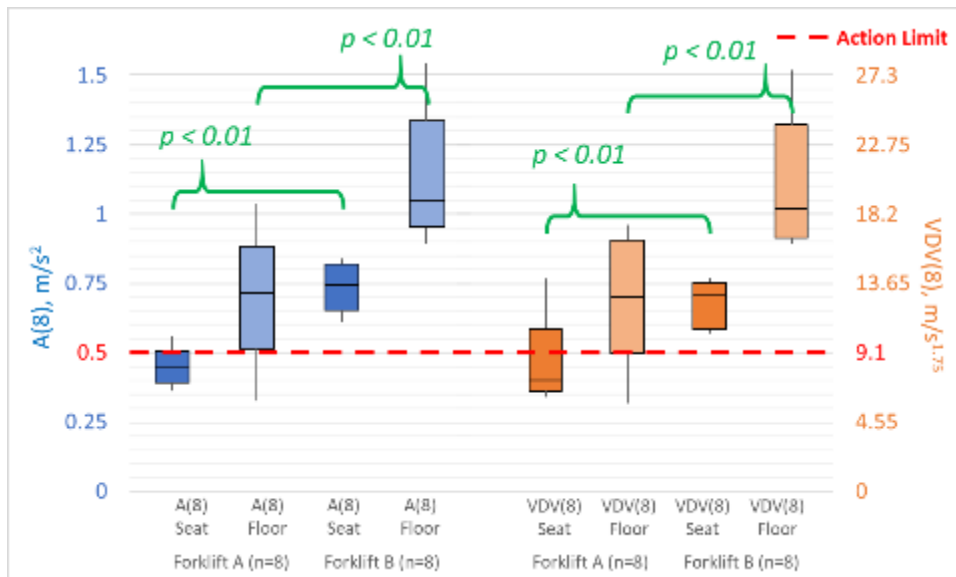


Figure 2.10. A(8) and VDV(8) WBV exposures between the forklift with (Forklift A) and without (Forklift B) the mast-based vibration damping system while operating the forklifts over the common route. The red dashed line indicates the European Union’s daily vibration action limits. The boxes indicate interquartile ranges; the horizontal line in the boxes are median values; whiskers indicate maximum and minimum values.

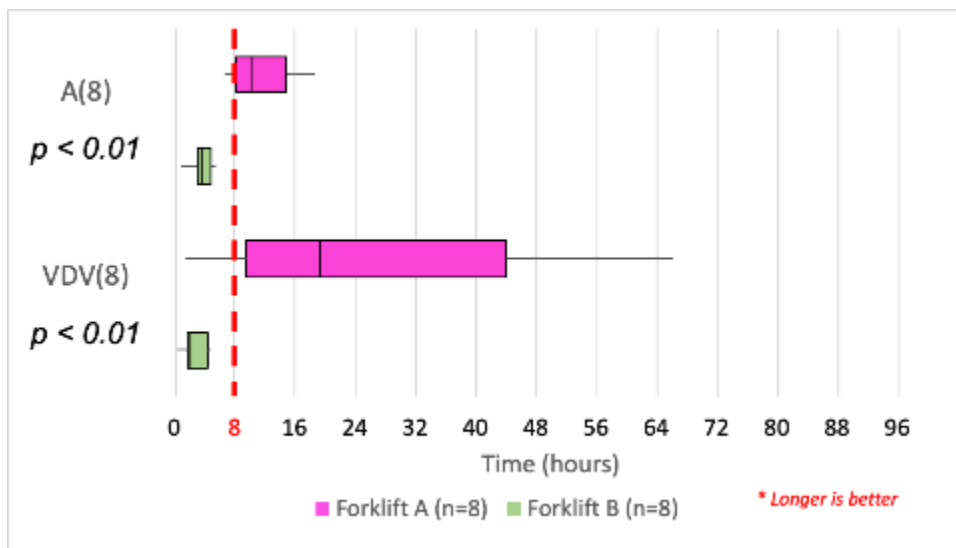


Figure 2.11. Time to action limit (TAL) based on A(8) and VDV(8) WBV exposures between the forklift with (Forklift A) and without (Forklift B) the mast-based vibration damping system while operating the forklifts measured while operating the forklifts over the common route. The boxes indicate interquartile ranges; the horizontal line in the boxes are median values; whiskers indicate maximum and minimum values.

Table 2.6. Comparison of the median (25th, 75th) common route A(8) and VDV(8) Seat Effective Amplitude Transmissibility (SEAT) between the forklift with (Forklift A) and without (Forklift B) the mast-based vibration damping system

Parameter	Forklift A (n=8)	Forklift B (n=8)	p-value
	Median (IQR)	Median (IQR)	
A(8) SEAT	59.8% (49.4, 95.8)	69.0% (62.1, 81.7)	0.51
VDV(8) SEAT	56.8% (47.3, 99.1)	64.4% (58.5 76.9)	0.61

2.3.5 Comparison of the Power Spectral Densities and Transmissibilities between Forklifts with and without Mast-based Vibration Damping System

Power spectral densities (PSDs) based on the WBV exposures measured at the floor of the forklifts while operated over the common route indicated that the most energy was centered at 4 Hz for both forklifts (Figure 2.12). The vibration energy at 4 Hz in Forklift B was almost three times higher compared to Forklift A. Moreover, a second energy peak was present between 8 - 9 Hz in both forklifts. The vibration energy at 8 – 9 Hz in Forklift B was about five-fold higher than that in Forklift A. The PSDs based on the seat-measured vibration showed the primary dominant (1st peak) frequency was 3 Hz at which the energy was about five times higher with Forklift B compared to Forklift A.

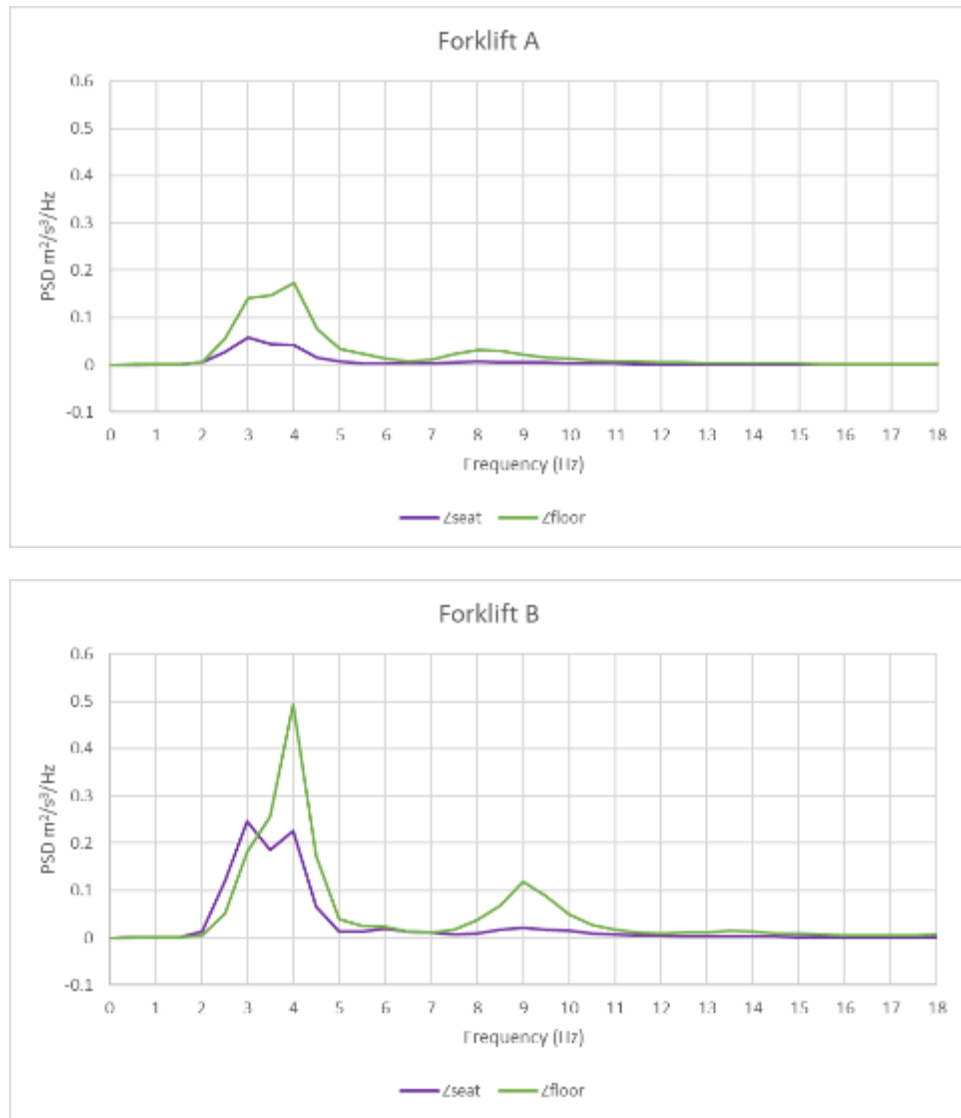


Figure 2.12. The median weighted Power Spectral Densities of the forklift with (Forklift A) and without (Forklift B) the mast-based vibration damping system when operated at the common route.

Seat transmissibility, as a function of frequency, showed that the seat in Forklift A (pink line) began to attenuate the floor-measured vibration energy at 2 Hz and continued to dampen vibrations at progressively higher frequencies (Figure 2.13.). In contrast, the seat in Forklift B amplified the floor-measured vibration between 0.5 and 3.25 Hz; otherwise, it attenuated the vibration at the higher frequencies.

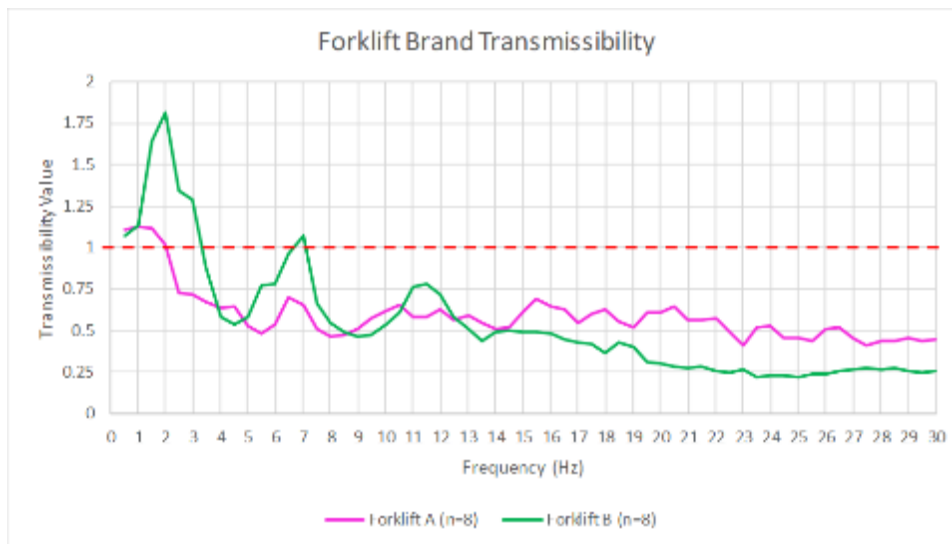


Figure 2.13. Transmissibility of the WBV exposures between the driver seat and forklift floor compared by the forklift with (Forklift A) and without (Forklift B) the mast-based vibration damping system measured while operated over the common route.

2.3.6 Perceived Musculoskeletal Pain Levels Compared between Operators of Forklifts with and without Mast-based Vibration Damping System

The baseline (pre- forklift operation) self-reported pain levels compared between the two forklifts showed no significant differences (p 's > 0.17) (Figure 2.14). Comparing the pain levels between forklifts in each body location after forklift operation also showed no significant differences (p 's > 0.11) (Figure 2.15.). The operators of Forklift B reported higher pain levels in all the body locations compared to the responses by the Forklift A operators. The pain level changes in pre- and post-forklift operation between the forklifts showed statistical significance in the shoulder and knees ($p = 0.04$), but the rest of the body locations showed no significant differences (p 's > 0.21) (Figure 2.16.). The median pain level changes in all body locations, except the knees, indicated no changes in pre- and post-forklift operations for both forklifts, where a slight positive change in the knees for Forklift B was shown.

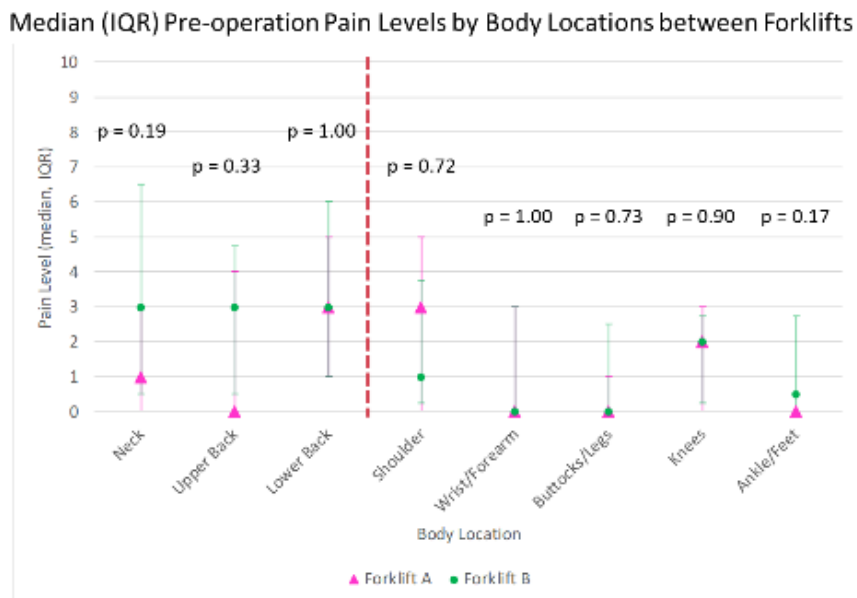


Figure 2.14. Comparison of the median (25th and 75th) pre-forklift operation self-reported musculoskeletal pain levels by body locations between the forklift with (Forklift A) and without (Forklift B) the mast-based vibration damping system. p-values represent the statistical difference between the two forklift groups per each body location; Left of the red dashed line are the three upper body regions along the spine and right are the rest of the body locations

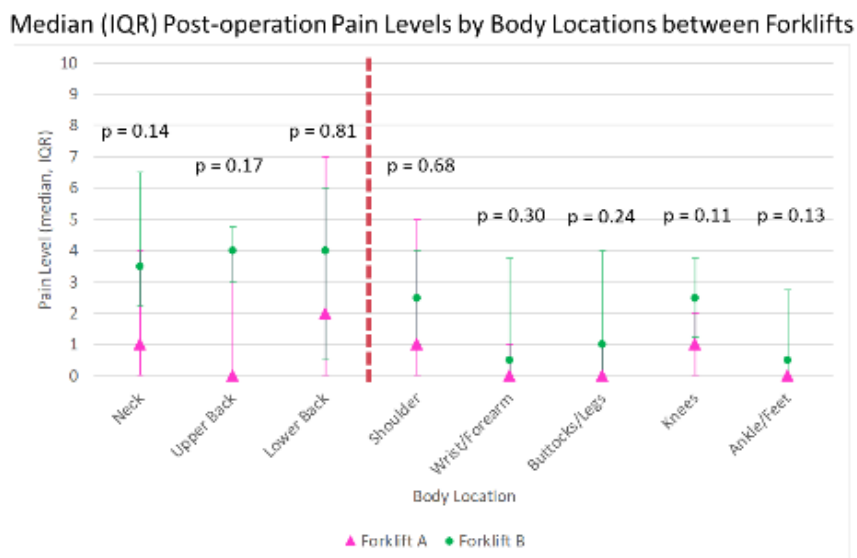


Figure 2.15. Median (25th and 75th) of post-forklift operation self-reported musculoskeletal pain levels by body locations between the forklift with (Forklift A) and without (Forklift B) the mast-based vibration damping system. p-values are the statistical difference between the two forklift groups per each body location; Left of the red dashed line are the three upper body regions along the spine and right are the rest of the body locations

Median (IQR) Pain Level Changes (Delta) between Forklifts by Body Locations

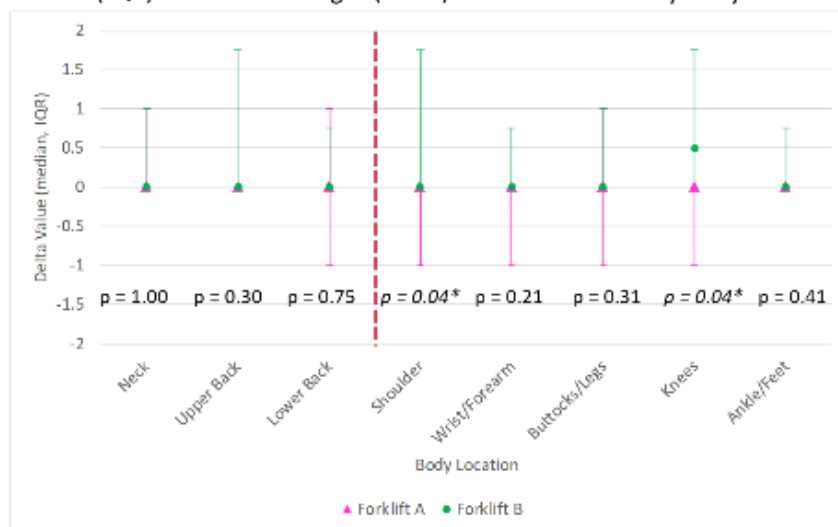


Figure 2.16. Comparison of the median (25th and 75th) self-reported musculoskeletal pre- and post-operation pain level differences (delta) between the forklift with (Forklift A) and without (Forklift B) the mast-based vibration damping system. p-values are the difference of the delta between the two forklift groups in each body location, the positive delta values (more than 0) represent an increase in pain level change, and the negative delta values (less than 0) represent a decrease of pain level change between before- and after- operation; Left of the red dashed line are the three upper body regions along the spine and right are the rest of the body locations

2.4 DISCUSSION

2.4.1 *Study Summary and Key Findings*

This is one of the few studies that has assessed WBV exposures and the associated pain in forklift operators. The study specifically aimed to compare two types of forklifts: those with a mast-based vibration damping system versus those without such a system. With respect to WBV exposure differences, A(8) and VDV(8) exposures were found to be lower when operating forklifts with a mast-based vibration damping system. Below, we discuss other important findings from this study, including factors that were found to be related to forklift WBV, the comparison of the measured WBV exposures to established standards, the relationship between WBV and pain reported by forklift operators, and the potential implications for important stakeholders (e.g., forklift manufacturers, procurement, operators, and injury prevention programs), and study limitations.

2.4.2 *Differences in Cab Floor Vibration Levels between the Forklifts with or without Mast-based Vibration Damping System*

This study's comparison of the mast-based vibration damping system is unique and different from previous forklift studies that have compared a variety of factors that potentially relate to WBV exposures, including driving surfaces, driving speed, drivers' posture, and seat suspension types (Motmans, 2012). Hoy et al. (2005) Blood et al. (2010). However, no previous study has considered a vibration damping system on the forklift, which may have the potential to reduce overall exposure to WBV in forklift operators.

In the current study, with the measurements at the floor of the forklift, there was clear evidence for the reduction of vibration from mast-based damping system, as both the A(8) and VDV(8) exposures – one representing average vibrations, and the other better-representing

impulse vibrations, respectively – were lower. Because the front axle is part of the mast-based vibration damping system and the top of the mast is further attached to the chassis via a suspension system, these design features appeared to contribute to reducing the vibration levels measured at the forklift floor.

The ability of the forklift with the mast-based vibration damping system to reduce the input vibration from the floor can be beneficial as previous forklift research has described the potential for uneven surfaces to create shocks, bumps, and jolts that contribute to WBV (Motmans, 2012) and surface quality, in general, has been found to be one of the primary predictors of vibration exposure across various vehicle types (Cann, Salmoni, & Eger, 2004; Chen, Chen, Liu, Chen, & Pan, 2009). Moreover, managing impulsive shocks from rough surfaces was one of the main motivations for the previous study by Blood et al. (2010) for their study of mechanical versus air suspension seats for forklifts. Additionally, it is important to acknowledge that forklift operations often involve frequent loading and unloading of pallets, which may create impulsive vibration exposures (Hoy et al., 2005; Waters et al., 2007). Due to the variable factors and exposure to impulsive shocks, it is important to recognize that the floor-based A(8) and VDV(8) measures observed in this study were both lower with the mast-based vibration damping system compared to the forklift without this structure. This suggests that this technology may benefit operators by reducing vibration from entering the forklift cabin.

2.4.3 *Differences in the Seat-measured Whole-Body Vibration Exposures between the Forklifts with or without Mast-based Vibration Damping System*

The current study result showed that both seat-measured A(8) and VDV(8) WBV exposures were lower than floor-based measures for both types of forklifts. While seat-measured A(8) exposures were always significantly lower in the mast-based damping system forklift than

the forklift without the technology, there was essentially no difference in impulse vibration [VDV(8)] between the type types of forklifts, which suggests that the WBV difference that was observed at the floor was handled differently by the seat suspensions. Moreover, the attenuation between the floor and seat measurements observed in the present study was consistent with the Blood et al. (2010) study for mechanical suspension seats (i.e., 45% and 35% attenuation for A(8) and VDV(8) measures, respectively). The vibration measured at the top of the seat depends on the input vibrations coming from the floor, the damping qualities of the seat as well as other factors, such as operator weight (Blood et al., 2010). Therefore, although it was not the primary goal of the current study, the findings provide further evidence for the role of mechanical suspension seats in effectively attenuating vibration. However, despite the mechanical seat's effectiveness, the seat-measured VDV(8) exposures for both forklifts were high and exceeded the daily vibration action limits. As demonstrated in the Blood et al. (2010) study, air suspension seats may be considered (if applicable) to further reduce forklift operators' exposure to WBV.

2.4.4 *Other Factors Related Whole-Body Vibration Exposures in this Study*

The magnitude of z-axis WBV measured in this study was lower than the levels measured in other studies. Hoy et al. (2005) measured A_w WBV with a mean (SD) of 0.57 (0.124) m/s^2 and VDV of 34.0 (7.837) $m/s^{1.75}$ at the seat, and Blood et al. (2010) measured A_w with a mean (SE) of 0.48 (0.07) m/s^2 and VDV of 17.6 (2.4) $m/s^{1.75}$ at the seat when the forklifts were operated during the regular work shift. This study found a mean (SE) levels of A(8) of 0.23 (0.03) m/s^2 and VDV(8) of 10.4 (1.0) $m/s^{1.75}$. for the forklift with a mast-based damping system and A(8) of 0.40 (0.05) m/s^2 and VDV(8) of 12.0 (1.0) $m/s^{1.75}$ for the forklift without the technology. However, the measurements of the mast-based damping system match other previous studies that included measures of this particular model (Schust et al., 2015, A(8) of 0.27 m/s^2).

While other studies have discussed other factors that influence WBV exposures such as the engine, forklift structure, seat, tires, road surface, speed, load weight, and tasks (Blood et al., 2010; Kumar, 2004) – factors that have been categorized as relating to the environment, the truck, and the driver (Motmans, 2012), the strength of the current study is that by employing the same operators, driving the same forklifts, on a standardized route, many of these confounding factors were controlled for in the study design.

The current study noticed that the cumulative impulsive WBV exposures [VDV(8)] were higher when accounting for both inactive/active periods of the regular work shift compared to when the forklift was always moving/actively operated. The higher VDV(8) exposures were likely due to the artificially generated peak impulsive vibration exposures created during the inactivity/idle periods when the forklift operators returned to their forklift and sat down on the seat pad accelerometer. Characterizing the VDV(8) exposures when the forklift is moving appears to eliminate this plumping artificial impulsive events that may occur when operators return to their forklifts and sit on their seats after a period of inactivity. Based on this observed interaction between the vibration parameters, the VDV(8) WBV exposures would be most accurately characterized based on the measurements when the forklift was always moving/actively operated.

2.4.5 *Comparison to Whole-Body Vibration Standards*

While US-based WBV standards do not exist, comparing the study's WBV measurements to existing EU standards allows for a practical interpretation of the role of a mast-based damping system in forklifts to reduce workplace injury. Relative to the 8-hour EU action limits, after accounting for duty cycle, the A(8) at the seat of both forklift types did not exceed the action limit of 0.5 m/s^2 . However, the impulsive WBV VDV(8) levels at the seat of both types of forklifts

exceeded the action limit of $9.1 \text{ m/s}^{1.75}$. These results indicate that operators of both types of forklifts were potentially at risk due to the high impulsive vibration exposures.

We discuss below in section 2.4.6 practical approaches to reduce this risk.

2.4.6 *Relationship between Whole-Body Vibration and Forklift Operator Self-Reported Pain*

Although the study found self-reported short-term pain levels suggestive of less pain among those operating the forklift with the mast-based vibration damping system compared to those operating the other forklift, the differences were not statistically significant. The lack of significant findings respect to pain may reflect some limitations of the current study design compared to other studies. For example, the current study involved a relatively small population of workers, the work history of the operators was not assessed to determine the extent of their previous work with either of the types of forklifts or other types of forklifts, and the pain was not assessed as a chronic condition, but rather just before/after the work shift in the study. In contrast, Gopanna et al.'s (2015) study assessed chronic pain for a much larger population (N=47) forklift operators than the current study. Most of the pain reported in that study was for chronic lower back pain, with 85% of the respondents reporting lower back discomfort 1-2 times per week, and many reporting pain severities as moderate or above. Similarly, the cross-sectional study conducted by Hoy et al. (2005), assessed pain in a larger group of workers (N=46) than the present study, and focused on chronic pain rather than on short-term shift-related pain, and found that lower back pain was more prevalent amongst forklift drivers than non-drivers. And a retrospective cohort study of the association between forklift operation and pain conducted by Flodin et al. (2018) involved 140 forklift operators. The power to detect statistically significant differences in pain between the two forklift types in the present study would probably require a different study design

comparing groups of long-time users of one versus the other type of forklift, and questioning about chronic pain.

Despite the lack of significance in differences between self-reported short-term pain in the present study, the PSD findings provide some insight into the risk for lower back pain. The primary dominant frequency was at approximately 3 Hz (ranging between 2 and 6 Hz) at the seat, and about five times higher for the forklift without the mast-based vibration damping system compared to the one with the mast-based vibration damping system. This frequency is close to the resonate frequency of the human spine, which studies have indicated has a principal frequency between 4–12 Hz (Ryan, 2018). Therefore, the differences in vibration near these frequencies from using a mast-based vibration damping system forklift may have some long-term benefits in reducing the risk of developing chronic lower back pain.

2.4.7 *Study Limitations*

The present study has a number of limitations, which are important to acknowledge. First, the study was not able to entirely control for the measurement environment and variables such as driving style, condition of each forklift, tire wears, and variable road surfaces, as the measurement was performed during the forklift operator's regular work shift. These inconsistencies result in additional variability in the WBV exposures measured among subjects and reduced statistical power to assess differences between forklift types. Second, as mentioned above, the small sample size of workers recruited for the study may have influenced the lack of significance of self-reported pain between the two forklifts. However, the lack of significance may also be related to the relatively short-term pain shift-based pain assessment.

2.4.8 *Implications for Forklift Operator Injury Prevention Programs*

Despite the aforementioned limitations, this study provides novel evidence in support of using mast-based vibration damping system forklifts to reduce WBV. However, relevant to the development of forklift operator injury prevention programs, the study also observed that EU action limits for VDV(8) would be exceeded with either of the two types of forklifts that were studied in this particular work context. For this reason, forklift injury prevention programs should be more holistic in their design, and leverage WBV control strategies that span the hierarchy of controls, including the substitution of equipment to ensure that forklift operator has access to effective vibration damping technologies such as mast-based vibration damping, seat damping, etc.; and opportunities to reduce their exposure time via administrative controls. This advice is consistent with evidence from other WBV studies, such as Motmans' (2012), which found that after evaluating WBV reductions achievable through either improved driving surfaces, altering driving speed, or changing seat suspension technology – none would be effective alone in reducing WBV below standards. Therefore, integrating multiple injury prevention strategies that are deemed to be cost-effective, while maintaining productivity remains a practical objective for workplace managers.

2.5 CONCLUSION

In conclusion, this study demonstrated that there was WBV exposures difference existed between the two different forklifts evaluated, where Forklift A with the mast-based vibration damping system performed better on limiting the WBV exposures to the operators. Forklift A maintained lower forklift-generated vibration exposures throughout the work shift, as well as transmitting a smaller amount of vibration from the forklifts to the operators. In addition, the operators of Forklift A experienced less musculoskeletal pain after their job tasks. Considering the lower WBV exposures as well as a lower risk of low back pain development, utilizing Forklift A may provide a better forklift operating experience for those operators at the manufacturing site during regular work shift. Based on the present study result, further evaluation of WBV exposures reduction by the forklift vibration damping systems, peculiar for each forklift in the market on benefiting forklift operators. Proceeding from the present study findings, it would be merit to construct further evaluation of understanding the mechanism of the forklift vibration damping systems as well as its contribution toward reducing WBV exposures.

Chapter 3. DIFFERENCES IN WHOLE-BODY VIBRATION EXPOSURES BETWEEN FORKLIFTS WITH PNEUMATIC AND SOLID TIRES

3.1 INTRODUCTION

Professional vehicle operators are exposed to various risk factors associated with musculoskeletal disorders (MSDs), including prolonged sitting, awkward posture, and repetitive exposure to whole-body vibration (WBV) (Bovenzi, 2010; Hoy et al., 2005; Magnusson et al., 1996; Wegscheider, 2014). Among these factors, exposure to WBV is consistently identified as a leading cause of MSDs, especially low back pain (Bernard et al., 1997; Massimo Bovenzi et al., 2006; Waters et al., 2008).

Forklift operators are exposed to high levels of WBV, which is in part due to the tires used on the forklifts (Cvetanović, Djekić, & Stojković, 2013; Malchaire et al., 1996; Verschoore et al., 2003). The stiffness of the forklift tire may play a role in the attenuation of vibrations (Jönsson, 2005; Motmans, 2012; Viruet et al., 2008). For example, Lemerle & Mistrot (2001) found an inverse relationship between vibration attenuation effect and level of tire stiffness. Also, different tire types may affect stiffness, and thereby WBV. For example, previous studies found evidence that pneumatic-tire forklifts with less stiffness had lower WBV exposures compared to solid-tire forklifts with higher stiffness (Joubert, 2002b; Zucco & Gomes, 2009).

In addition to the stiffness and WBV considerations, there are other factors that influence the forklift tire choices. Solid tires are highly resistant to puncture and are beneficial for extreme applications, including construction sites and debris-filled workplaces. However, the lack of

flexibility of the tire provides the least comfortable ride, making the operator more vulnerable to experiencing the vibrations.

In contrast, due to their flexibility, pneumatic tires provide a softer ride and better traction to control the vehicle. However, they are more susceptible to puncture under rough road conditions or contact with sharp objects or debris, which leads to higher maintenance costs and more frequent replacement compared to the solid tires (Berndtson, 2016). Therefore, the selection of forklift tire type not only needs to consider vibration damping effects, but also driver comfort, longevity, and the prevention of possible failures that may limit the duration of the forklift operation.

Although a number of studies have evaluated the performance of forklift tires with respect to WBV exposures, the majority of these previous studies were conducted under prescribed, controlled operating conditions. Therefore, these controlled studies may not directly translate to practical forklift operation conditions as real environments vary in operating speed, road conditions (a mixture of both smooth and rough road surfaces with varying debris), and operation tasks.

Another potential limitation of previous studies is their focus on evaluating the WBV exposures only at the top of the forklift seat, which makes it difficult to differentiate the damping effect of the tire versus the effect of the seat.

The current study addresses the aforementioned limitations by evaluating different tire types in a more practical way that is more representative of actual day-to-day forklift operators' work conditions, as well as in a way that isolates the effects of different tire types from the potential attenuation of the seat. Specifically, the purpose of the current study is to determine the effect of different tire types (pneumatic vs. solid tires) on the WBV exposures during the actual forklift operation in a field setting. The study compares WBV exposures between forklifts of the same

make and model equipped with either solid rubber or pneumatic-tires when the forklifts are operated over a mixture operating condition. *It was hypothesized that WBV exposures experienced by the forklift operators operating forklifts with solid and pneumatic would be different.* The results of this study are discussed in terms of their impact on assisting procurement managers to choose appropriate forklift tire types for protecting the health of forklift operators.

3.2 METHODS

3.2.1 *Subjects*

A total of 15 professional forklift operators (all males) in a company's manufacturing facilities based in Seattle, WA, and Everett, WA, were recruited via flyer solicitations. All subjects were informed about the study objective, procedures, possible risks, and benefits. All subjects gave their informed consent prior to their participation.

3.2.2 *Forklifts and Tire Types*

Due to the restricted availability of forklifts from which to collect measurements, WBV characteristics of the two types of forklift tires were measured at different site locations using the same model forklifts (Model H100, Hyster-Yale, Cleveland, OH) (Figure 3.1.). Both forklifts, which were regularly used at both manufacturing sites, had the same load capacity of 5 tons and were equipped with the same mechanical suspension seat (FLM 1815, Sears Seating, Davenport, IA) (Figure 3.2.).

The forklifts were operated with two different types of tires: pneumatic tires (XZM, Michelin tire, Clermont-Ferrand, France) or solid tires (M2, Trelleborg AB, Trelleborg, Sweden). Of the 15 participants, five subjects based in Seattle, WA, operated forklifts with pneumatic tires, and ten subjects based in Everett, WA, operated forklifts with solid tires. To assess potential differences between the groups, important demographic, and work history data were collected (Appendix A) and statistically compared using the Wilcoxon signed-rank test (Table 3.1.). No significant differences were found in the demographics between the two groups.

Table 3.1. Subject demographic information [median (25th, 75th percentile)] by forklift tire groups. P-values were obtained from the Wilcoxon signed-rank test.

	Pneumatic tire (n=5)	Solid tire (n=10)	<i>p-value</i>
	Median (25 th , 75 th)	Median (25 th , 75 th)	
Age (year)	51.0 (34.5, 57.0)	41.0 (34.3, 50.5)	0.32
Operating Experience (year)	22.0 (6.6, 29.6)	10.4 (7.0, 23.0)	0.58
Weight (kg)	107.3 (87.7, 122.5)	105.5 (92.8, 132.0)	0.78
Height (cm)	185.4 (183.5, 185.4)	181.6 (175.3, 186.1)	0.25
BMI	31.6 (25.5, 35.8)	33.6 (30.2, 36.6)	0.52



Figure 3.1. Forklift (Hyster-Yale H100) used for two experimental groups: pneumatic tire (n = 5) and solid tire (n =10)

3.2.3 Whole-Body Vibration Data Collection

For the pneumatic tire group, three subjects among the five were asked to repeat the measurements on different pneumatic tire forklifts, so that eight unique forklift/subject combinations were collected. For the solid tire group, ten subjects operated one designated forklift, and five of the ten subjects repeated the measurements on different solid tire forklifts so that a total

of 15 unique forklift/subject combinations were obtained. Raw unweighted acceleration data were collected according to the ISO 2631-1 WBV standard using a seat-pad tri-axial accelerometer (Model 352B41; PCB Piezotronics, Depew, NY) placed on the driver seat, and a single-axis accelerometer (Model 352C33; PCB Piezotronics, Depew, NY) magnetically mounted on the floor of the forklift cabin. Both accelerometers were connected to a data recorder (DA-40; Rion Co. LTD, Tokyo, Japan) to collect the vibration data at a sampling rate of 1,280 Hz. A global positioning system (GPS) data logger (Model CR-Q1100P; Qstarz Co., Taipei, Taiwan) was placed inside the cabin to measure forklift speed and location data at 1 Hz (Figure 3.2.).

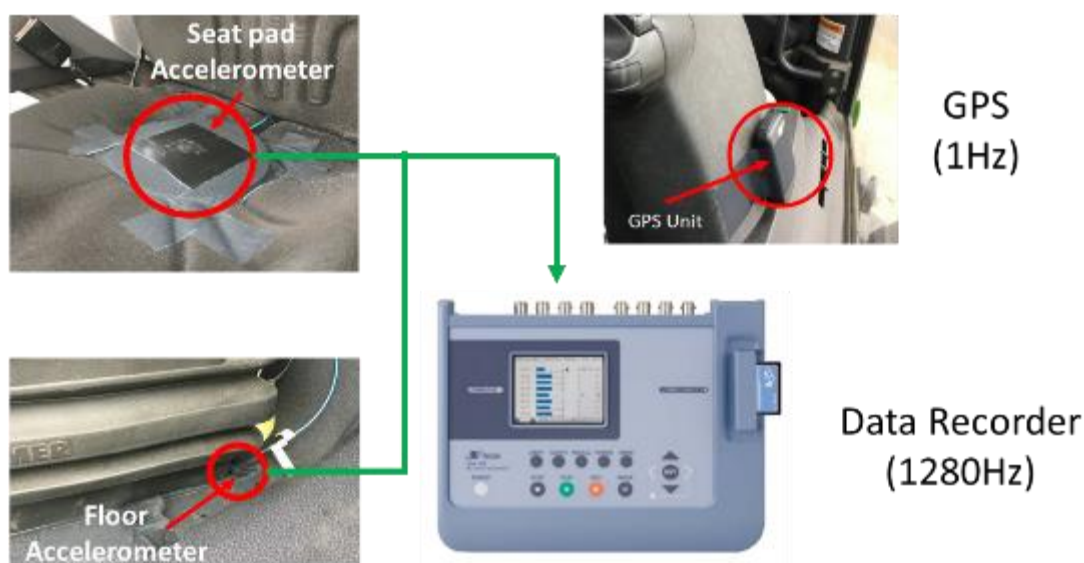


Figure 3.2. WBV measurement instrumentation

3.2.4 Whole-Body Vibration Data Processing

Regular Work Shift Data Processing

Following the methods previously described (Blood, Rynell, & Johnson, 2011), the collected raw acceleration and GPS data were merged using custom-built LabVIEW computer programs (Version 2018; National Instruments, Austin, TX). The frequency weightings were

applied to the combined data files to calculate the weighted average acceleration (A_w), and vibration dose values (VDV) per ISO 2631-1 (1997). The A_w and VDV values were normalized to represent daily (8-hr) exposures: $A(8)$ and $VDV(8)$. $A(8)$ and $VDV(8)$ values were compared to the European Union Directives (EU Directive Provisions, 2002) daily exposure action limit [$A(8) = 0.5 \text{ m/s}^2$; $VDV(8) = 9.1 \text{ m/s}^{1.75}$] to determine health implications.

In addition, the possible duration the forklifts could be operated before reaching the EU daily vibration action limits for $A(8)$ and $VDV(8)$ were determined using the following equations:

Time to Action Limit (TAL) for $A(8)$:

$$TAL(A[8]) = \left(\frac{0.5}{A(8) \text{ exposure value}} \right)^2 * 8 \quad (3.1)$$

Time to Action Limit (TAL) for $VDV(8)$:

$$TAL(VDV[8]) = \left(\frac{9.1}{VDV(8) \text{ exposure value}} \right)^4 * 8 \quad (3.2)$$

The Seat Effective Amplitude Transmissibility (SEAT) value is the percentage of WBV exposures measured at the seat relative to the vibrations measured at the floor of the vehicle/base of the seat (Equation 3.3). The SEAT value is a performance measure of the driver seat, indicating the degree to which the vibration exposures are attenuated or amplified by the forklift seat.

Seat Effective Amplitude Transmissibility (SEAT):

$$SEAT (\%) = \frac{\text{seat measured WBV exposure value}}{\text{floor measured WBV exposure value}} * 100 \quad (3.3)$$

Because the pneumatic and solid tire forklifts were operated at two different sites, it was essential to determine whether the operating conditions that are known to affect vibration exposures were comparable between the study sites. To determine whether the forklifts with the two tire types were operated under similar conditions, the median speed (km/h), operating duration (min), the proportion of operating (moving) and idle (non-moving) times of the forklifts were

calculated using the GPS data and compared between the two tire groups (Table 3.2.). The operating (moving) time was determined when the forklift speed was greater than 1 km/h or GPS coordinates changed within 60 seconds. The idle (non-moving) time was identified when the GPS coordinates did not change for 60 seconds or longer.

Common Terrain (Route) Comparison

Despite the similarities between the study sites in operating speed, duration, and duty cycle (proportion of moving and non-moving times), there may have been potential between-site differences in other nuisance factors such as road surface. To minimize the effects of potential nuisance factors on the vibration exposures, we identified a 60-second segment of the common route which had similar road surfaces (roughness and pavement type) and all the forklift traveled over (yellow routes in Figure 3.3). The vibration data from this common route were processed and analyzed using the same methods described above.

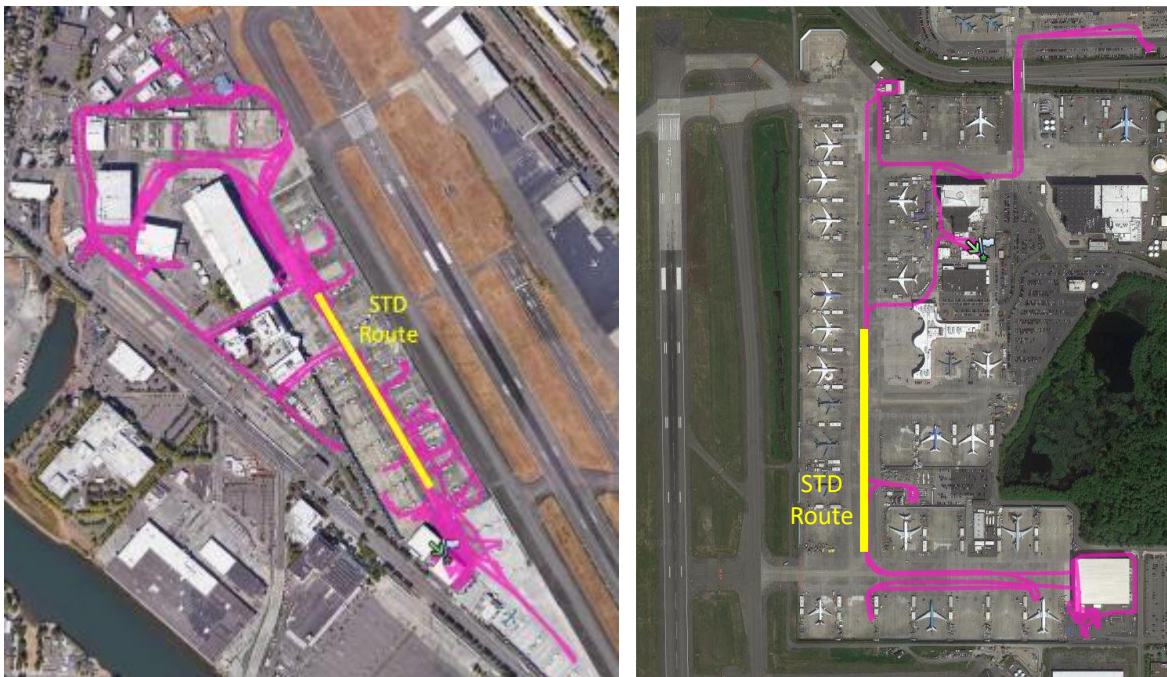


Figure 3.3. Map of typical forklift operating routes (pink) and the selected 60-second common route (yellow) for each Seattle, WA. (left) and Everett, WA. site (right)

Analyzed Data Types

A(8), and VDV(8) exposures were compared between two tire types based on the following three operating conditions: (1) during the operator's regular work shift which involved both activity (forklift movement) and inactivity (the forklift being idle or stationary); (2) during forklift movement, which would account for potential differences in the duty cycle of forklift operation and downtime (activity and inactivity); and (3) over the common routes, which would minimize the measurement differences between the two different sites.

3.2.5 Power Spectral Density and Transmissibility Analysis

Based on the 60-second common route segment files, Power Spectral Densities (PSDs) were analyzed as the measure of vibration's power content by frequency ($\text{m}^2/\text{s}^3/\text{Hz}$). Using a LabVIEW custom-built analysis program (Version 2018; National Instruments, Austin, TX), the vibration energy contents were summarized relative to the frequency range of 0 to 18 Hz with a frequency resolution of 0.5 Hz. The frequency range was selected based on the dominant vibration transmitting frequency range of the forklift below 20 Hz (Viruet et al., 2008). The median weighted PSDs from each forklift tire type were compared at the floor and seat of both forklifts. In addition, forklift seat transmissibility (the amount of energy that was transferred between the floor and seat) was evaluated and compared over the frequency range (0 to 20 Hz) for both pneumatic and solid tire forklifts. The transmissibility values refer to the ratio of the PSDs measured at the seat and floor: the value greater than 1 represents the amplification of the floor-measured vibrations at the seat, and the values less than 1 represent the attenuation of the floor-measured vibrations at the seat.

3.2.6 *Subjective Musculoskeletal Pain*

Self-reported musculoskeletal pain in eight body locations (neck, shoulder, upper back, lower back, buttocks/legs, wrist/hand, knees, and ankle/feet) were collected using a 10-point visual analog scale questionnaire (Kim, Dennerlein, et al., 2018; Kim et al., 2016; Kim, Zigman, et al., 2018) before and after the regular shift (Appendix B). With verbal anchors, the point scales were categorized as 0 being "no pain at all" and 10 being "the worst pain you can imagine."

3.2.7 *Statistical Analysis*

The independent and dependent variables of the current study are as follows:

- Independent variables:
 - Forklifts tire type: pneumatic tires or solid tires
- Dependent variables:
 - WBV exposures [A(8) and VDV(8)]
 - Time to action limits (TAL)
 - Seat Effective Amplitude Transmissibility (SEAT)
 - Power Spectral Density and Transmissibility ratio
 - Self-reported musculoskeletal pain levels in each body location experienced by the forklift operators

All dependent variables were summarized with median and interquartile range value (25th and 75th percentile), given the small sample size and their non-normality. Wilcoxon signed-rank tests (JMP Version 15; SAS Institute; Cary, NC) were used to determine whether there were any differences in WBV exposures, time to action limits, and SEAT between the two forklift tire type groups. In addition, the self-reported musculoskeletal pain levels were analyzed using the

Wilcoxon signed-rank test to determine whether the pain levels differed in each body location before and after forklift operation between the two forklift tire type groups. Statistical significance was noted when a p-value was less than 0.05.

3.3 RESULTS

3.3.1 Determination of Predominant Exposure Axis

As WBV exposures were predominant on the Z-axis for both pneumatic and solid tire forklifts (Figure 3.4.), the z-axis WBV exposures were compared between the two tire groups per the ISO 2631-1 WBV standard.

3.3.2 Comparison of Forklift Operating Speed and Duration between Two Forklift Tire Types

The duration and speed of the full-shift and moving-only measurements were compared to determine the comparability of the WBV exposures between two tire groups (Table 3.2.). No significant differences in the duration and speed indicated that operating conditions of the pneumatic- and solid-tire forklifts were similar.

Table 3.2. Comparison of forklift operation [median (25th, 75th)] between the forklift with pneumatic and solid tires

		Pneumatic-tire (n=8)	Solid-tire (n=15)	<i>p-value</i>
		Median (IQR)	Median (IQR)	
Forklift Operating Duration	Duty cycle (%)	37.5% (27.9, 56.2)	47.9% (37.9, 71.8)	0.21
	Only Moving (minute)	78.4 (60.2, 105.4)	65.6 (47.2, 107.3)	0.70
	Moving and Non-moving (minute)	211.4 (176.4, 235.2)	172.2 (133.1, 237.3)	0.35
Speed (km/h)	Only Moving	11.0 (7.2, 14.3)	11.5 (9.5, 12.4)	0.92
	Moving and Non-moving	4.2 (2.9, 5.4)	5.3 (3.6, 8.3)	0.11

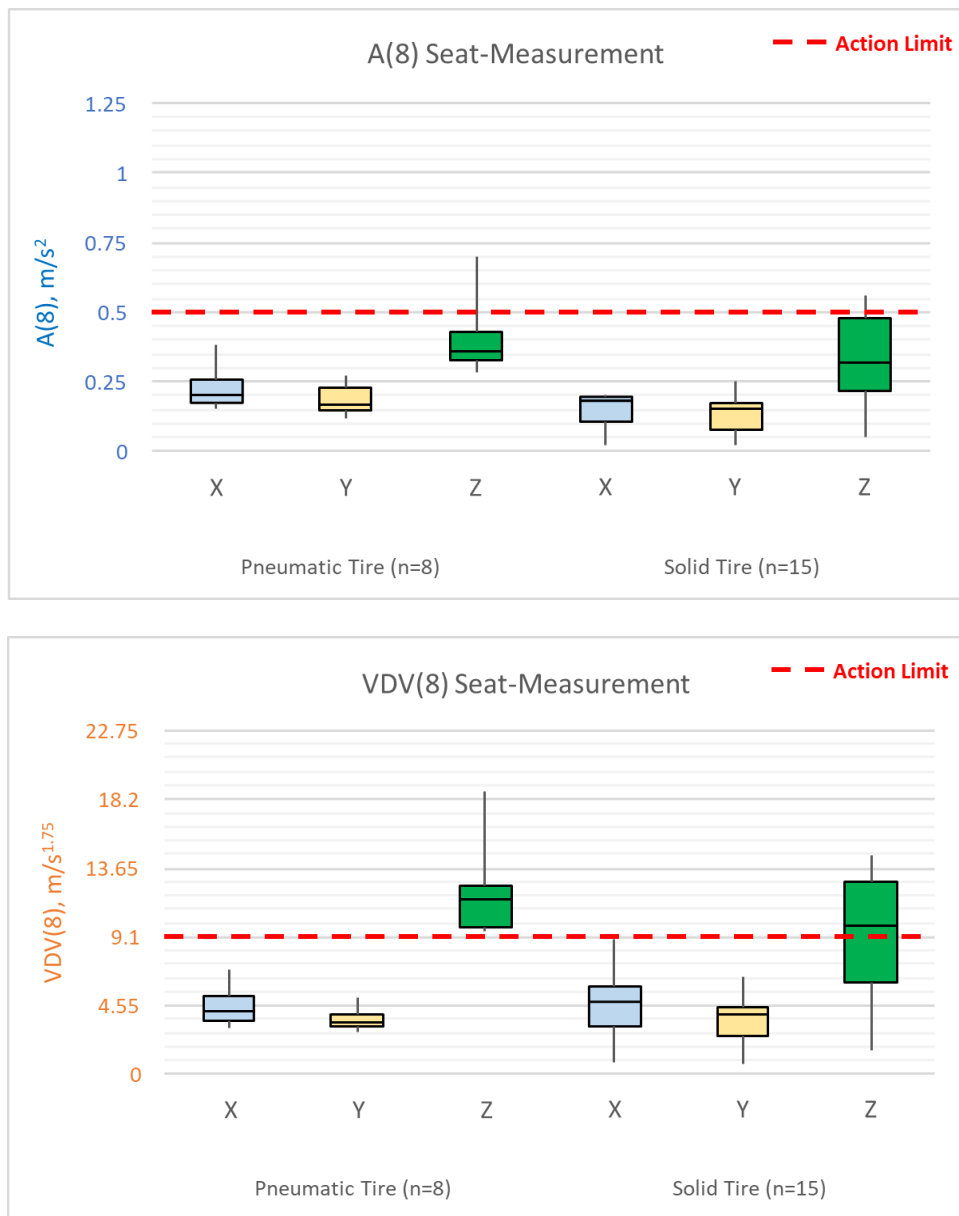


Figure 3.4. A(8) and VDV(8) exposures by pneumatic- and solid-tire forklifts for the fore-aft (X), lateral (Y), and vertical (Z) axis. Exposures were expressed relative to the European Union's daily vibration action limits (red dashed line). The boxes indicate interquartile ranges; the horizontal line in the boxes are median values; whiskers indicate maximum and minimum values.

3.3.3 *Whole-Body Vibration Comparisons between Pneumatic and Solid-Tire Forklifts during the Whole Regular Shift*

The A(8) and VDV(8) exposures during regular work shift showed no significant differences in WBV exposures between the two forklift tire groups (p values > 0.23) (Figure 3.5.). However, the floor-measured vibrations with the solid-tire forklifts resulted in slightly higher A(8) and VDV(8) compared to the pneumatic-tire forklifts. At the same time, the seat-measured exposures were slightly higher with the pneumatic-tire forklifts. The median seat-measured A(8) exposures for both the pneumatic and solid-tire forklifts did not exceed the EU daily vibration action limit of 0.5 m/s^2 , whereas the median VDV(8) exceeded the EU daily vibration action limit of $9.1 \text{ m/s}^{1.75}$.

The median seat-measured WBV exposures were used to calculate the time to reach the action limits (TAL) (Figure 3.6.). Both A(8) and VDV(8) TAL showed no significant differences between the two forklift tires ($p = 0.29$, $p = 0.23$, respectively). The A(8) TAL showed that forklifts could be operated longer than 8 hours with both pneumatic and solid tires. However, based on the VDV(8) WBV exposures, forklifts can be operated around 3.5 hours and 6 hours with pneumatic and solid tires, respectively, before reaching to the action limits.

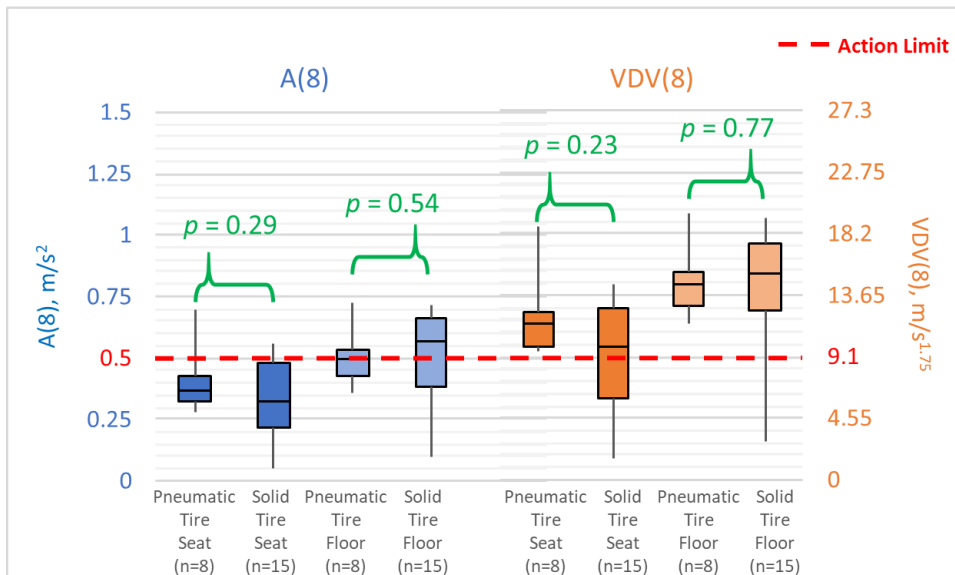


Figure 3.5. $A(8)$ and $VDV(8)$ exposures by forklift tire types. The red dashed line indicates the European Union's daily vibration action limits. The boxes indicate interquartile ranges; the horizontal line in the boxes are median values; whiskers indicate maximum and minimum values.

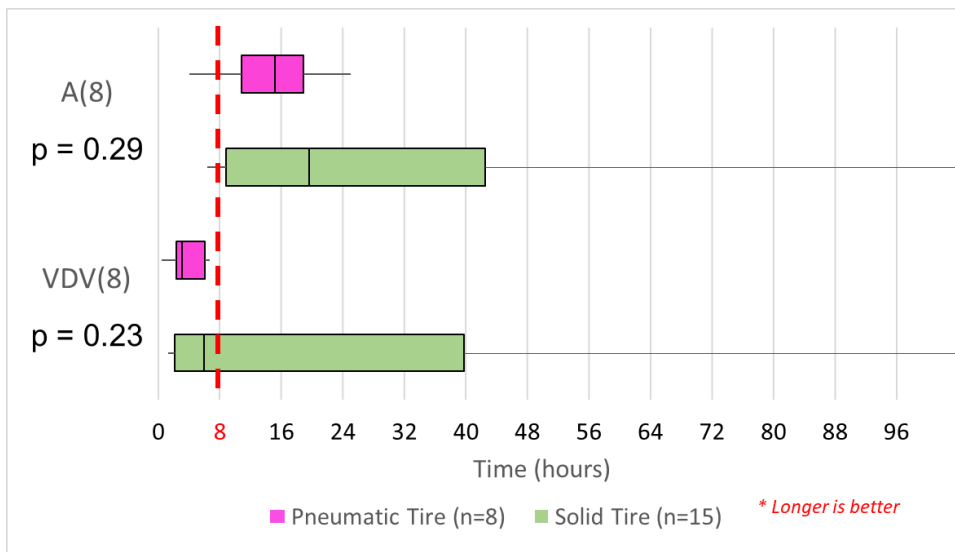


Figure 3.6. Time to action limit (TAL) based on $A(8)$ and $VDV(8)$ WBV exposures by forklift tire types measured during the regular work shift. The boxes indicate interquartile ranges; the horizontal line in the boxes are median values; whiskers indicate maximum and minimum values.

3.3.4 Whole-Body Vibration Comparisons between Pneumatic and Solid-Tire Forklifts while the Forklifts were in Motion

The WBV exposures were compared between the pneumatic and solid-tire forklifts only when forklifts were in motion ($> 1\text{km/h}$) (Figure 3.7.). There were no differences in the floor-measured A(8) and VDV(8) vibrations between the two forklift tires ($p = 0.32$ and $p = 0.58$, respectively). The pneumatic-tire forklifts had higher seat-measured A(8) WBV exposures than the solid-tire forklifts ($p < 0.01$), whereas the seat-measured VDV(8) WBV exposures were not different between two forklift tires ($p = 0.26$). Only the seat-measured A(8) WBV exposures of the pneumatic-tire forklift exceeded the European Union's daily vibration action limit. Based on the A(8) TAL result, the solid-tire forklifts could be operated about 5 hours longer than the pneumatic-tire forklifts before reaching to the action limit ($p < 0.01$) (Figure 3.8.). The A(8) and VDV(8) Seat Effective Amplitude Transmissibility (SEAT) values were different between the two tire types (Table 3.3.). Based on the A(8) and VDV(8) SEAT values, the same model seat performed better in the solid-tire forklifts compared to the pneumatic-tire forklifts.

Table 3.3. Comparison of median (25th, 75th) A(8) and VDV(8) Seat Effective Amplitude Transmissibility (SEAT) based solely on the periods of forklift movement/operation during the regular work shift

Parameter	Pneumatic tire (n=8)	Solid tire (n=15)	p-value
	Median (IQR)	Median (IQR)	
A(8) SEAT	76.6% (60.9, 83.4)	56.3% (50.9, 74.7)	0.09
VDV(8) SEAT	75.3% (57.9, 82.8)	58.6% (41.8, 68.1)	0.06
Avg Speed (km/h)	11.00 (7.20, 14.33)	11.51 (9.45, 12.35)	0.92

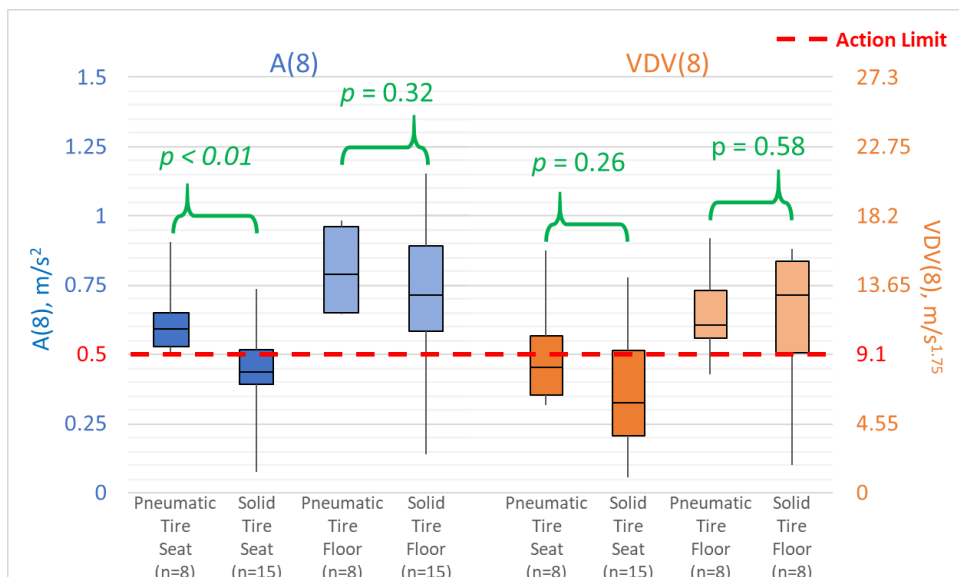


Figure 3.7. A(8) and VDV(8) WBV exposures by forklift tire type while each pneumatic and solid-tire forklift was in motion. The red dashed line indicates the European Union's daily vibration action limits. The boxes indicate interquartile ranges; the horizontal line in the boxes are median values; whiskers indicate maximum and minimum values.

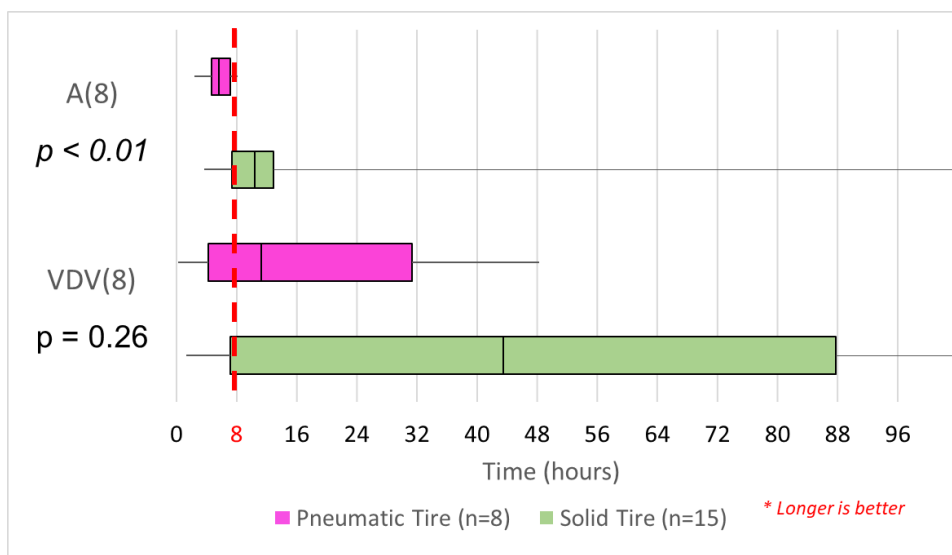


Figure 3.8. Time to action limit (TAL) based on A(8) and VDV(8) measured while each pneumatic and solid-tire forklift was in motion. The boxes indicate interquartile ranges; the horizontal line in the boxes are median values; whiskers indicate maximum and minimum values.

3.3.5 Whole-Body Vibration Comparisons between Pneumatic and Solid-Tire Forklifts while Travelling on the Common Route

As mentioned in the methods section, the common routes will provide more conservative comparisons of WBV exposures by having similar road surface and operating speed ($p = 0.64$) between pneumatic and solid-tire forklifts (Table 3.4.).

Table 3.4. Comparison of the median (25th, 75th) common route A(8) and VDV(8) Seat Effective Amplitude Transmissibility (SEAT) and forklift speed between two forklift tire types

Parameter	Pneumatic tire (n=8)	Solid tire (n=15)	p-value
	Median (IQR)	Median (IQR)	
A(8) SEAT	70.3% (59.3, 81.2)	53.9% (45.9, 69.9)	0.12
VDV(8) SEAT	64.0% (58.2, 74.8)	50.2% (41.4, 60.6)	0.06
Avg Speed (km/h)	22.79 (21.86, 23.44)	22.53 (19.97, 22.99)	0.64

On the common route, the floor-measured A(8) and VDV(8) vibrations were significantly higher with the pneumatic-tire forklifts as compared to the solid-tire forklifts (Figure 3.9). Similarly, the seat-measured A(8) and VDV(8) WBV exposures were also significantly higher for the pneumatic-tire forklifts. A(8) WBV exposures measured at both forklift seats exceeded its EU daily vibration action limit, while only the pneumatic-tire forklift's VDV(8) exceeded the EU daily vibration action limit.

A(8) and VDV(8) TAL between two forklift tire groups showed a significant difference (Figure 3.10.). The A(8) and VDV(8) TALs of the pneumatic-tire forklifts were roughly two hours and four hours shorter compared to the solid-tire forklifts. The SEAT values showed that the seats in solid-tire forklifts reduced 11% more of the A(8), and 15% more of the VDV(8) vibrations generated by the forklift to the operators compared to the seats in pneumatic-tire forklifts (Table

3.4.). However, the difference of the SEAT values between two forklift tire types did not reach significance.

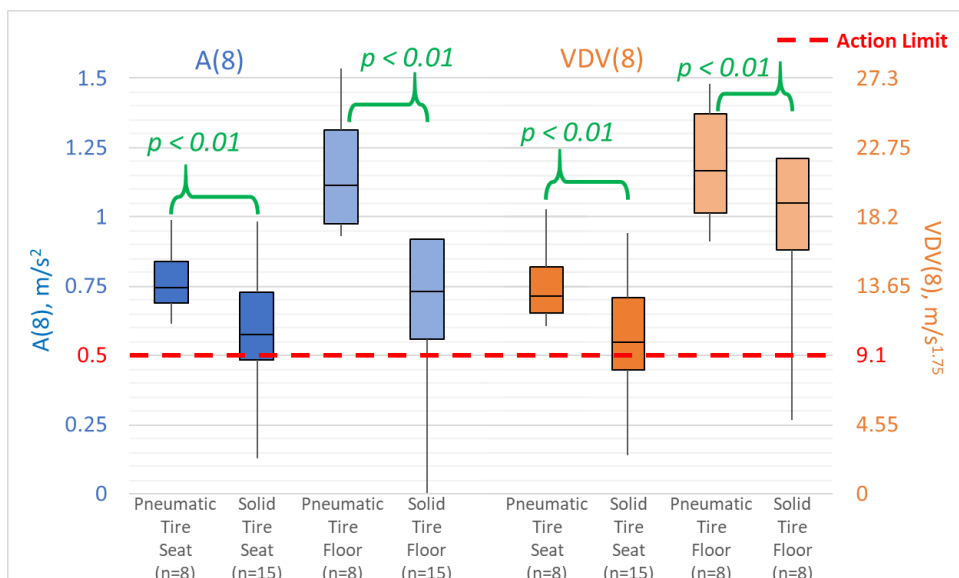


Figure 3.9. A(8) and VDV(8) exposures by forklift tire type while traveling on the common route. The red dashed line indicates the European Union's daily vibration action limits. The boxes indicate interquartile ranges; the horizontal line in the boxes are median values; whiskers indicate maximum and minimum values.

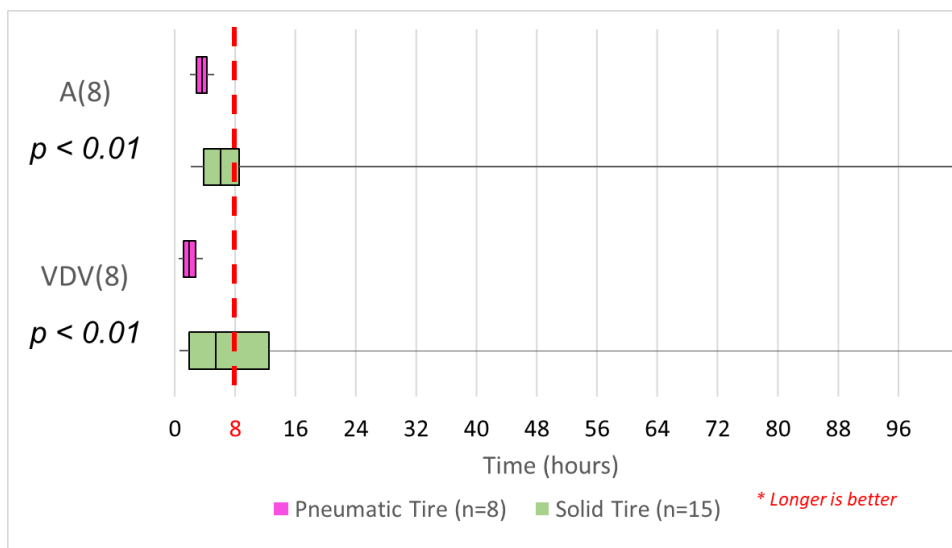


Figure 3.10. Time to action limit (TAL) based on the A(8) and VDV(8) exposures measured while traveling on the common route. The boxes indicate interquartile ranges; the horizontal line in the boxes are median values; whiskers indicate maximum and minimum values.

3.3.6 *Comparison of the Power Spectral Densities and Transmissibility between Pneumatic and Solid-Tire Forklifts*

Power Spectral Densities (PSDs) results based on the vibrations measured from the common route showed that most of the floor-measured vibration energy of the pneumatic-tire forklifts was centered at 4 Hz (Figure 3.11.). The floor-measured vibration energy of the solid-tire forklifts was centered at 5 Hz, and the vibration energy was slightly lower when compared to the pneumatic-tire forklifts. Also, the second energy peaks were at 9 Hz and 10.5 Hz for the pneumatic and solid-tire forklifts, respectively. In contrast, the measured vibration energy was about two-fold higher for the pneumatic-tire forklifts compared to the solid-tire forklifts. The PSDs based on the seat-measured WBV showed the primary dominant (1st peak) frequency was at 3 Hz, and 5.5 Hz for pneumatic and solid-tire forklifts, respectively, and the vibration energy was about 2-times higher with pneumatic-tire forklifts compared to solid-tire forklifts.

Figure 3.12. illustrates that the seats in the pneumatic-tire forklifts started to attenuate the floor-measured vibration energy around 3 Hz (pink line). In contrast, the identical seats in the solid-tire forklifts started attenuation around 3.5 Hz (green line). In addition, the peak amplification was greater in the seats on the pneumatic-tire forklifts (170% at 2 Hz) compared to the same seats on the solid-tire forklifts (145% at 1 Hz).

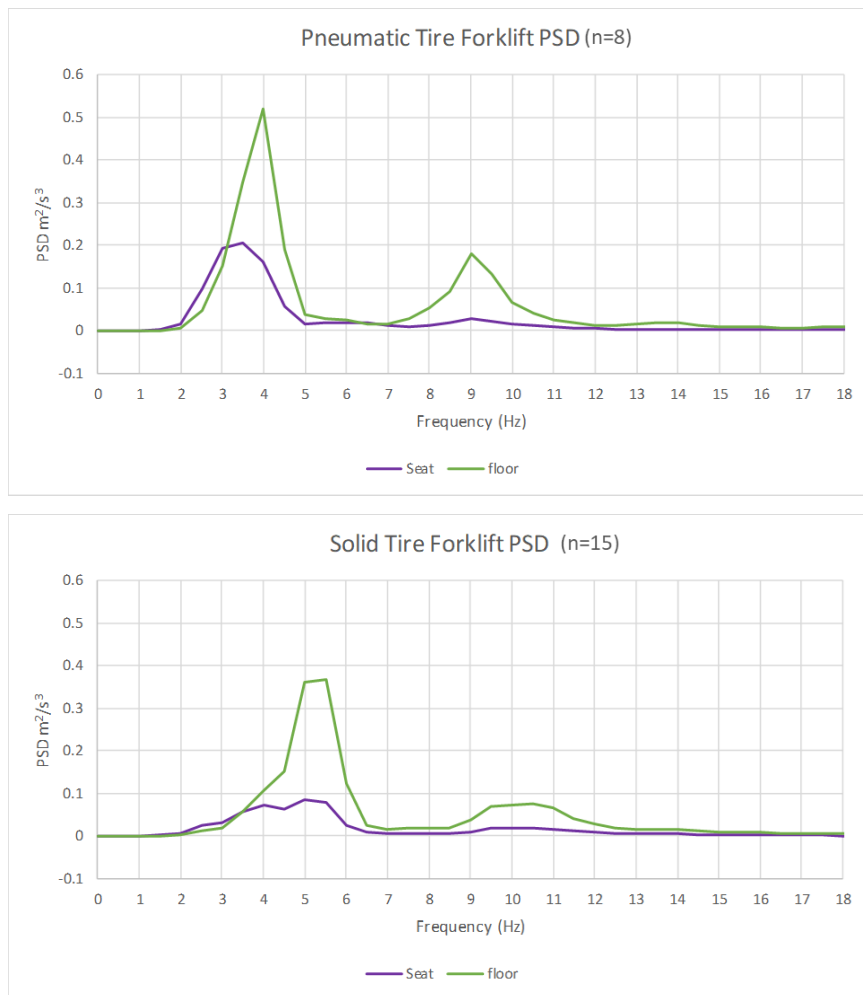


Figure 3.11. Comparison of the median weighted Power Spectral Densities between two forklift tire types when operated over the common route.

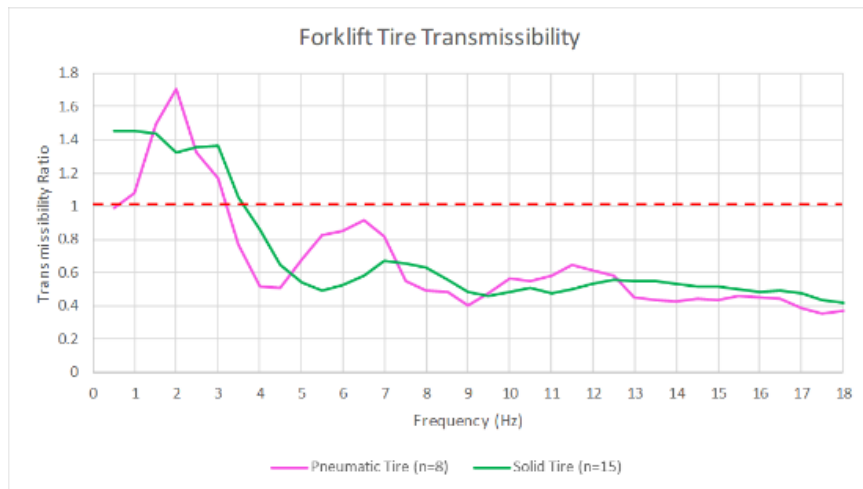


Figure 3.12. Transmissibility of measured vibrations between the forklift seat and floor compared by the pneumatic and solid-tire forklift groups while operated over the common route.

3.3.7 Perceived Musculoskeletal Pain Level Data Analysis

While the baseline (pre-forklift operation) self-reported pain levels showed no significant differences between the pneumatic and solid-tire forklift, the post-forklift operation pain levels were higher with the pneumatic-tire forklifts compared to the solid-tire forklifts (Figure 3.13). Nonetheless, the pain changes between pre- and post-operation in most body parts were significant in both the pneumatic and solid-tire forklift groups (Figure 3.15). Although the pain changes in the shoulders and knees reached the statistical significance, the changes were minimal.

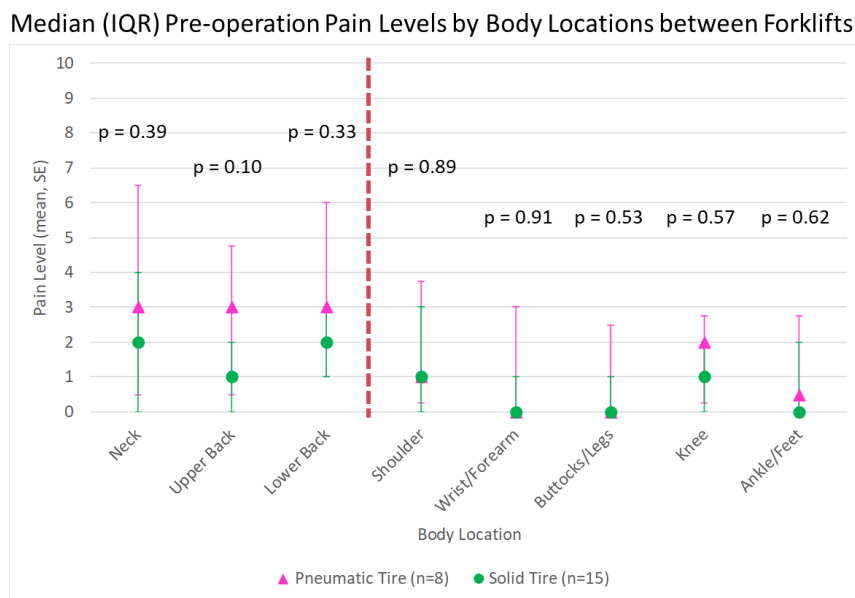


Figure 3.13. Comparison of the median (25th and 75th) pre-forklift operation self-reported musculoskeletal pain levels by body locations between the pneumatic and solid-tire forklift operators. P-values represent the statistical difference between the two forklift tire groups per each body location; Left of the red dashed line are the three upper body regions along the spine and right are the rest of the body locations

Median (IQR) Post-operation Pain Levels by Body Locations between Forklifts

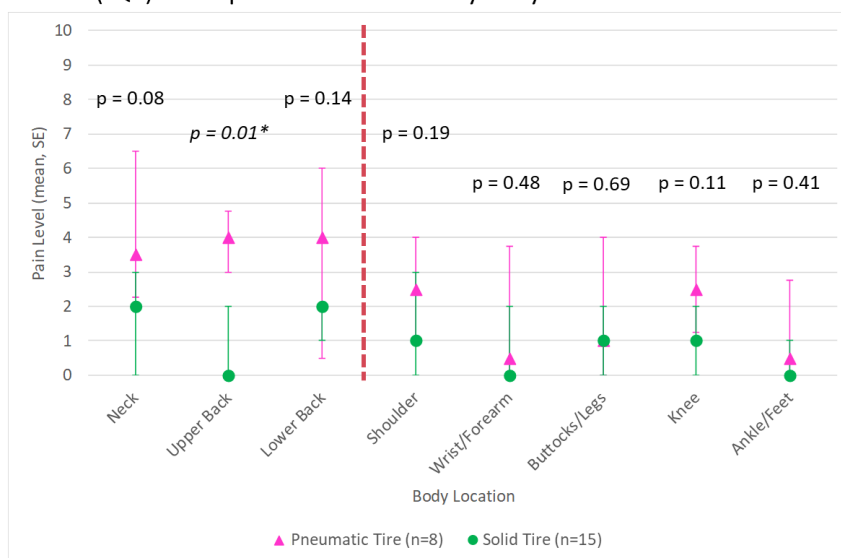


Figure 3.14. Comparison of the median (25th and 75th) post-forklift operation self-reported musculoskeletal pain levels by body locations between two forklift tire groups; p-values are the statistical difference between the forklift tire groups per body location; Left of the red dashed line are the three upper body regions along the spine and right are the rest of the body locations

Median (IQR) Pain Level Changes (Delta) between Forklifts by Body Locations

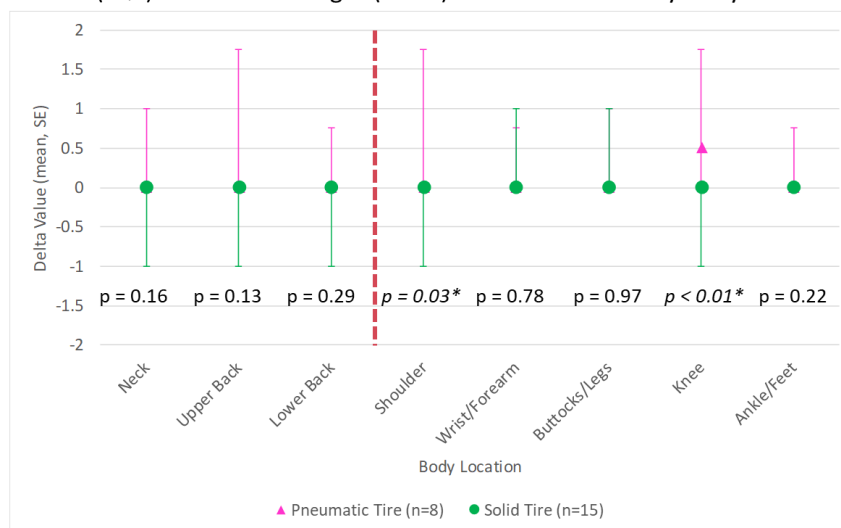


Figure 3.15. Comparison of the median (25th and 75th) self-reported musculoskeletal pre- and post-operation pain level differences (delta) between the two forklift tire groups; p-values are the statistical difference of the delta between the forklift tire groups per body location, the positive delta values (more than 0) represent an increase in pain level change, the negative delta values (less than 0) represent a decrease of pain level change between before- and after- operation; Left of the red dashed line are the three upper body regions along the spine and right are the rest of the body locations

3.4 DISCUSSION

3.4.1 *Study Summary and Key Findings*

The main objective of this study was to characterize realistic WBV exposures the professional forklift operators experienced during their actual regular work shift and to determine whether the WBV exposures were any different between pneumatic and solid-tire forklifts. The study identified that there was a difference in levels of WBV exposure between pneumatic and solid-tire forklifts. While the seat measurements indicated that the operators of pneumatic-tire forklifts experienced higher WBV exposures compared to operators of solid-tire forklifts, the floor-measured vibrations showed that the pneumatic-tire forklifts generated lower vibration during an 8-hour regular work shift. Below, we discuss the findings from the seat and floor measurements, the relationship between WBV and operators' reported musculoskeletal pain levels, and study limitations.

3.4.2 *Whole-Body Vibration Exposures Measured at the Seat*

The present study results showed that operators of pneumatic-tire forklifts experienced higher A(8) and VDV(8) WBV exposures compared to operators of solid-tire forklifts during the 8-hour regular work shift. This finding was similar to a previous study showing that pneumatic tires had higher WBV exposures measured at the top of a mechanical suspension seat compared to solid-tire forklifts (Malchaire et al., 1996). While both A(8) and VDV(8) seat measurements were higher in the pneumatic-tire forklifts, the floor-measured vibration of that forklifts were lower than solid-tire forklifts. This seat and floor measurement differences were shown by the SEAT results, where identical mechanical suspension driver seats were in both pneumatic and solid-tire forklifts, but the seats in solid-tire forklifts performed better. Moreover, the PSD analysis result provided

further evidence that depending on the resonance frequencies generated by each forklift tire types, the identical mechanical suspension driver seat performed differently, where the seat performed better in attenuating the vibration energy frequency generated by the solid tires. These findings are consistent with previous work by Malchaire et al. (1996), who also stated that the seat WBV exposures could vary depending on the type of the driver seat due to the different frequency range that each driver seat suspension can control. These study findings reinforce the importance of the driver seat performance in reducing WBV exposures in relation to the forklift-generated vibration, which includes tire type factors.

Our study result showed that all forklift operators experienced VDV(8) WBV exposures higher than the EU daily vibration action limits of $9.1 \text{ m/s}^{1.75}$, whereas A(8) WBV exposures were below the action limit of 0.5 m/s^2 during the 8-hour regular work shift, accounting for the duty cycle. Moreover, the higher VDV(8) and its associated shorter TAL indicated that the forklift operators were frequently exposed to the impulsive WBV, which was a main limiting factor for the allowable forklift operation time. This result showed that operators of either pneumatic or solid-tire forklifts were both more vulnerable to impulsive VDV(8) WBV exposures during their day-to-day work shift, compared to continuous average A(8) WBV exposures.

3.4.3 *Vibrations Measured at the Floor of the Forklift Cabin*

The floor vibration measurements with pneumatic and solid-tire forklifts showed clear evidence of the vibration difference due to the tires. The study results of floor-measured vibration during an 8-hour regular shift showed that solid-tire forklifts generated higher vibration compared to the pneumatic-tire forklifts. Vibrations measured at the floor of the forklift cabin represents the overall forklift-generated vibrations due to the various forklift operating conditions (road surface and speed) as well as the forklift components (engine, structure, and tires) (Blood et al., 2010;

Kumar, 2004). Considering the measurements were collected from an identical forklift model, such measurements in this study represented the best means for comparing the performance of the forklifts with different tire types.

Although the floor-measured vibration during the 8-hour regular work shift was higher with solid-tire forklifts, contrasting results were found when the forklifts were operated over the common route. Despite the inconsistency, both measurement results provided evidence on identifying the difference between the two forklift tire types. The results for the 8-hour regular shift provide information relevant to determining appropriate forklift tire types for vibrations generated across a broader set of operating conditions, including various road conditions and tasks, during daily regular work shift. In comparison, the results for the common route provide information on the vibration that may be more readily compared between specific tire types. For example, the PSD analysis of the common route data in this study showed lower resonant frequencies and greater vibration power at primary and secondary resonance by the pneumatic-tire forklifts, which appears to be due to the pneumatic-tires amplifying the vibrations compared to the solid-tires. Therefore, measuring the level of vibration at the floor provided further understanding of how each forklift tire influenced the WBV exposures as well as determining the difference of the vibration between two forklift tire types. Without the floor measurements, the true sources of the WBV exposures, and the performance and impact of the seat suspension could not be known.

3.4.4 *Self-Reported Musculoskeletal Pain Levels Findings*

Although the results for self-reported musculoskeletal pain levels were not statistically significant in many body locations, they tended to indicate that the pain levels were higher for the drivers after operating either pneumatic or solid-tire forklifts. This was especially relevant for the upper body locations (neck, upper back, and lower back) among the pneumatic-tire forklift

operators. Operators experiencing higher forklift WBV exposures typically reported higher pain levels. This finding was consistent with a previous study that found reduced WBV via a seating intervention resulted in a greater than 25% reduction in low back pain (LBP) (Kim et al., 2015). Boshuizen et al. (1992) also stated that significantly higher LBP (12-month odds ratio of 2.2) was observed among the 242 forklift operators exposed to WBV exposures than 210 other workers who were not exposed to WBV. Moreover, the current study result was consistent with the previously stated dose-response relationships between LBP and WBV (Massimo Bovenzi, 2010; Hoy et al., 2005; Waters, Genaidy, Deddens, & Barrieria-Viruet, 2005). However, the small sample size and the method of assessing pain just prior to and immediately following the work shift—which did not account for the chronic nature of musculoskeletal pain—may have lowered the statistical power in this study.

3.4.5 *Study Limitations*

Despite this study's strengths, including characterizing the WBV exposures experienced by the forklift operators with two different forklift tire types during their regular work shift, and identifying the difference of the vibration between two tire types, there were limitations that may affect the interpretation and generalizability of the results. First, WBV exposures for each type of forklift tire were collected at two separate sites, which may have created variability in the WBV measurements due to the difference in measurement sites. In order to accommodate the comparability of the vibration measurements at these two sites, the duration of the measurements, percentage of duty cycle, and the speed of the forklift operations were compared between the two forklift tire groups. Although these comparisons showed similarity and provided some comparability, additional factors, such as age and condition of the forklifts and tires, should be further compared in order to provide better comparability.

Second, the small sample size of operators recruited for the study may have influenced the lack of significance as well as generating large variability with regard to WBV exposures. In conjunction with the small sample size, the lack of significance of the self-reported pain levels may also be related to the relatively short-term shift-based pain assessment. Despite the small sample size, the current study was able to show some significant differences in the WBV exposures between two forklift tire types. However, increasing sample size and observation duration of the forklift operation may increase the statistical power for determining the vibration differences between pneumatic and solid-tire forklifts as well as identifying the meaningful clinical influence on reducing health risk by the forklift tires.

Lastly, collecting data using one type of forklift and with only male forklift operators may limit the generality of the pneumatic and solid-tire forklifts WBV exposures in the industry. Despite this limitation, the study was conducted with a number of forklift operators that represent the demographic of male forklifts, in which the operators had similar BMI levels compared to other previous studies (Blood et al., 2010; Deshmukh, 2009; Hoy et al., 2005). Also, the forklift model used in this study was one of the most popular forklifts used in the US, with total revenue of \$3174 million in sales in the year 2018 (McCrea, 2019).

3.5 CONCLUSION

In conclusion, this study identified that there was a WBV exposure difference between pneumatic and solid-tire forklifts, wherein operators of pneumatic-tire forklifts experienced higher WBV exposures compared to those who operated solid-tire forklifts during a regular work shift. However, the difference of floor-measured vibrations between pneumatic and solid-tire forklifts were inconsistent, depending on the type of data. The common route data analysis—including PSDs—demonstrated that the type of forklift tire likely contributed toward the difference of WBV exposures between the forklifts. The present study was able to explain the impact that the forklift tire type had on the WBV exposures. Moreover, the SEAT values also clarified the performance of the driver's seat and the roles that tires play in the transmission of WBV exposures. Based on the present study result, more detailed consideration of the relative stiffness, damping performance, construction, and general condition of the forklift tires (age, wear, etc.) and its influences on seat performance would further illuminate the WBV exposures comparison between the different types of tires.

Chapter 4. CONTRIBUTIONS OF THE SEAT TOP AND SEAT SUSPENSION IN MITIGATING FORKLIFT OPERATOR WHOLE-BODY VIBRATION EXPOSURES

4.1 INTRODUCTION

Studies have consistently shown that exposure to whole-body vibration (WBV) is associated with the onset and development of lower back pain (LBP) in vehicle operators (Teschke, AM, Davies, & Ju, 1999; Tiemessen et al., 2007; Waters et al., 2007). In particular, the risk of LBP for forklift operators is two times higher compared to other workers who are not exposed to WBV (Motmans, 2012; Viruet et al., 2008; Waters et al., 2008). While the majority of the forklift operators' exposure to WBV results from driving, these operators are also exposed to impulsive shocks and jolts that can occur during loading and unloading. These impulsive exposures can contribute to the degeneration of the lumbar spine (A. G. Mayton, Kittusamy, Ambrose, Jobes, & Legault, 2008). This may explain the disproportional high risk of musculoskeletal disorders, especially in the low back regions among forklift operators.

In most vehicles such as passenger cars, trucks, and buses, WBV exposures are mitigated by vehicles' suspensions, seat suspensions, and seat cushions (Ahmadian et al., 2002; J. C. Chen et al., 2003; Kim et al., 2016; Thamsuwan, Blood, Lewis, Rynell, & Johnson, 2012). However, forklift suspensions are designed to have minimal dampening for load stability while transporting heavy loads (Jönsson, 2005). As limited dampening may not protect the forklift operators from the vibration exposures, the driver seat (i.e., suspension and cushion) is particularly important in mitigating forklift operators' exposure to WBV. Among the various engineering interventions, seat suspensions have extensively been studied and identified as one of the most effective methods for reducing WBV in forklift operators (Blood et al., 2010; Lemerle & Mistrot, 2001; Wegscheider,

2014). These studies showed that pneumatic suspension seats were more effective in reducing WBV compared to mechanical suspension seats or suspension-less seats. In addition, the materials, composition, and stiffness of the seat cushions are important factors affecting WBV exposures (Ahmadian et al., 2002; Mehta & Tewari, 2010). The previous study by Mehta & Tewari (2010) found that the differing composition of the foam with stiffness used in various seat cushions, such as high resiliency (HR) polyurethane foam with TDI (toluene diisocyanate) and MDI (methylenediphenyl diisocyanate), has been found to affect reducing the amount of transmitted WBV exposures.

Although these previous studies on the seat suspensions and cushions provide important implications in WBV mitigation during forklift operations, the independent evaluation of the suspension and cushion does not shed light on the relative contribution of each of the seat component in reducing the overall vibrations that reach the operators. The relative contribution of the seat suspension and cushion is particularly important in forklifts because the seat suspension choices for the forklifts are limited to low-profile suspensions due to the low head clearance of forklift cab. Such limited options in the seat suspensions may create needs for developing better performance foams or alternative suspension that can meet the low-profile requirement in forklifts.

To understand the relative contribution of the seat suspension and cushion in reducing WBV, this study measured vibration at the vehicle floor, suspension top, and seat top to quantify the amount of vibration attenuated by the mechanical seat suspension and seat cushion during regular forklift operation. *It was hypothesized that the amount of vibration attenuated by the seat suspension and seat cushion would be different.* Quantifying the respective performance characteristics of the seat suspension and seat cushion may inform their combined design to optimize the effective reduction of WBV exposures for forklift operators.

4.2 METHODS

4.2.1 *Subjects*

A total of ten forklift operators (all males) employed in a manufacturing facility were recruited by solicitation. Prior to participation, all subjects were informed about the study, the possible risks and benefits of participation, and provided their informed consent to participate in the study. Subjects' work history and demographic information of the subjects were collected (Appendix A) and summarized in Table 4.1.

Table 4.5. Subjects' demographic information [Median (IQR)] of the forklift operators

N=10		Median (IQR)
Age (year)		41.0 (34.3, 50.5)
Operating Experience (year)		10.4 (7.0, 23.0)
Body Mass (kg)		105.5 (92.8, 132.0)
Height (cm)		181.6 (175.3, 186.1)
BMI		33.6 (30.2, 36.6)
Forklift Operating Duration (minutes)	Only Moving	65.6 (47.2, 107.3)
	Moving and Non-moving	172.2 (133.1, 237.3)
Speed (km/h)	Only Moving	11.5 (9.5, 12.4)
	Moving and Non-moving	5.3 (3.6, 8.3)

4.2.2 *Forklifts*

WBV exposures were measured from forklifts of the same model and load capacity (Model H100, Hyster-Yale, Cleveland, OH) used at a manufacturing site (Figure 4.1.). All forklifts were equipped with the same mechanical suspension seats (FLM 1815, Sears Seating, Davenport, IA), and solid tires (M2, Trelleborg AB, Trelleborg, Sweden).

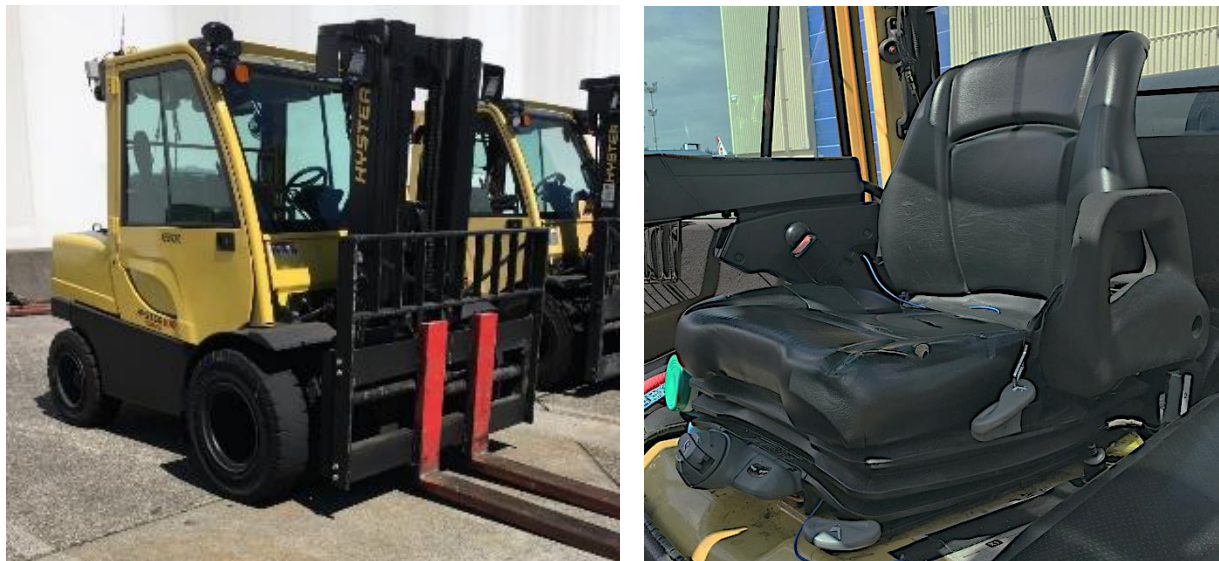


Figure 4.1. Forklift model (Hyster-Yale H100, Left), and Mechanical suspension seat (Sears Seating FLM 1815, Right) used in the study

4.2.3 *Whole-Body Vibration Data Collection*

Among the ten subjects, five subjects were asked to complete the second measurement on the same model but different forklifts. With the repeated measurements by the five subjects on a different forklift, 15 different unique forklift/subject combinations were collected. Based on the ISO 2631-1 (1997) WBV standard, WBV exposures were collected using a tri-axial seat-pad accelerometer (Model 356B41; PCB Piezotronics, Depew, NY) mounted on top of the seat. A second tri-axial accelerometer (Model 352C33; PCB Piezotronics, Depew, NY) was magnetically mounted on the top of the suspension (i.e., just below the seat cushion); and a third single-axis accelerometer (Model 352C33; PCB Piezotronics, Depew, NY) was magnetically mounted on the floor of the forklift cabin. Accelerometers were connected to the data recorder (DA-40; Rion Co. LTD, Tokyo, Japan) to record the vibration data at a sampling rate of 1,280 Hz. A portable global positioning system



Figure 4.2. Whole-Body Vibration data collection instrumentation with three accelerometers

4.2.4 Whole-Body Vibration Data Processing

Regular Work Shift Data Processing

Referring to the methods previously used by Blood et al. (2011), the collected vibration and GPS data were combined into one single file, using the LabVIEW program (Version 2018; National Instruments, Austin, TX). As described in ISO 2631-1 (1997), combined raw, unweighted acceleration data file was further processed and applied with vibration weightings to estimate weighted average acceleration (A_w) and vibration dose values (VDV). The A_w and VDV values were then normalized to 8-hr average weighted vibration exposures [$A(8)$] and Vibration Dose Values [$VDV(8)$] exposures. Finally, the $A(8)$ and $VDV(8)$ exposures were compared to the European Union Directives (E.U. Directive Provisions, 2002) daily exposure action limit [$A(8) = 0.5 \text{ m/s}^2$; $VDV(8) = 9.1 \text{ m/s}^{1.75}$], to understand the possible risk of adverse health outcomes due to the level of the WBV exposures.

Based on the WBV exposures at the three different levels (floor, top of the suspension, top of seat), for relative comparison purposes, the duration of time to reach the E.U. daily vibration action limits were calculated and compared across the three levels using following equations:

Time to Action Limit (TAL) for A(8):

$$TAL(A[8]) = \left(\frac{0.5}{A(8) \text{ exposure value}} \right)^2 * 8 \quad (4.1)$$

Time to Action Limit (TAL) for VDV(8):

$$TAL(VDV[8]) = \left(\frac{9.1}{VDV(8) \text{ exposure value}} \right)^4 * 8 \quad (4.2)$$

Based on the A(8) and VDV(8) WBV exposures at each measurement location (Equation 4.3, 4.4, and 4.5), the Seat Effective Amplitude Transmissibility (SEAT) was calculated between the floor and top of the seat, the top of the suspension and the top of the seat and the floor and the top of the suspension. The SEAT value represents the ratio of the WBV exposures between two measurement locations in the forklift seat and characterizes how the seat cushion, seat suspension, or combination of seat cushion and suspension altered the forklift generated WBV exposures.

SEAT between the seat cushion and seat suspension:

$$SEAT(seat/sus) (\%) = \frac{\text{seat cushion measured exposure value}}{\text{seat suspension measured exposure value}} * 100 \quad (4.3)$$

SEAT between the seat suspension and floor:

$$SEAT(sus/floor) (\%) = \frac{\text{seat suspension measured exposure value}}{\text{floor measured exposure value}} * 100 \quad (4.4)$$

SEAT between the seat cushion and floor:

$$SEAT(seat/floor) (\%) = \frac{\text{seat cushion measured exposure value}}{\text{floor measured exposure value}} * 100 \quad (4.5)$$

To determine whether the forklift was being actively operated (moving) or idle, a second-by-second analysis was performed using the file containing the combined GPS and acceleration data. Based on the GPS information, WBV exposures could be differentiated and categorized based on when the forklift was active/moving or idle. Forklift movement/activity was based on when the forklift speed was greater than 1 km/h or GPS coordinates changed within a 60-second moving window.

Common Terrain (Route) Comparison

A common 60-second route that all forklift operators traveled over during their regular shift was identified using GPS coordinates (Figure 4.3., yellow line). The common route assessment allowed for comparisons of the WBV exposures while each forklift traveled over the same terrain, which controlled for a number of forklift operating factors, such as terrain conditions, operating tasks, and speed. WBV exposures from the common route were further processed and analyzed, as described above.

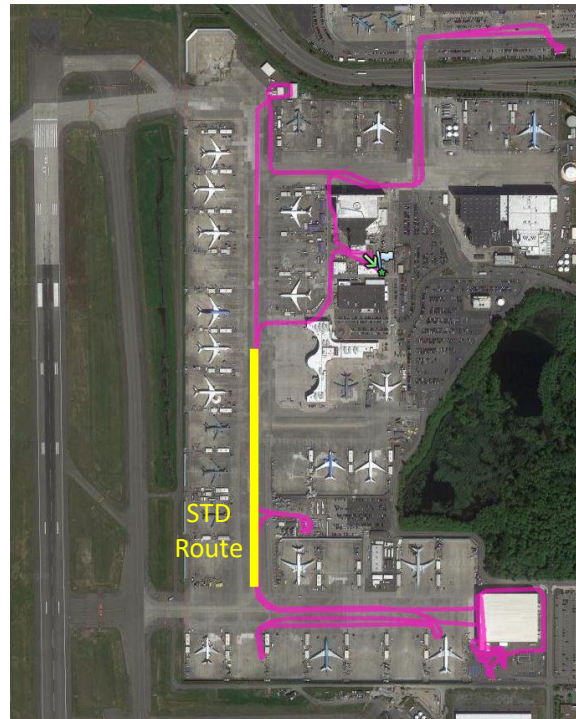


Figure 4.3. Map of typical forklift operating routes (pink) and the selected common route (yellow) at the manufacturing site

Analyzed Data Types

A(8) and VDV(8) WBV exposures at each level of the forklift seat (floor, seat suspension, seat cushion) were compared based on the following three types of operating conditions: (1) during the operator's regular work shift including both activity (forklift movement) and inactivity (the forklift being idle or stationary); (2) solely based on when the forklifts were active during the regular work shift (in operation and moving), accounting for potential duty cycle difference by each subject/forklift combination; and (3) while the forklifts were traveling over the common route (compared under the same operating conditions).

Forklift Operator's Body Mass Effect to Forklift Seat Performance

To better understand the effect of forklift seat performance as it related to differences in body mass across the forklift operators, the common route WBV exposures measurements were

compared across the subject's relative to the body mass of the subjects. In addition, calculated SEAT values for the seat top/suspension top, seat suspension/floor, and seat top/floor were compared across subjects, based on the body mass of the subjects.

4.2.5 *Power Spectral Density and Transmissibility Analysis*

Power Spectral Densities (PSDs), using common route data WBV exposures measurement, were calculated as the measure of vibration's power content by frequency ($\text{m}^2/\text{s}^3/\text{Hz}$). The LabVIEW computer program (Version 2016; National Instruments, Austin, TX) extracted and summarized the vibration energy content traveling through the measurement chain of the forklift seats by frequency range (0 – 18 Hz with a resolution of 0.5 Hz). The frequency range was selected based on the previous study's finding of the forklift dominant vibration-transmitting frequency range (below 20 Hz) (Viruet et al., 2008). The frequency content measured at the seat top, top of the seat suspension, and floor of each forklift was characterized and compared to determine the vibration frequency ranges, and the vibration amplitudes at the seat top, top of the seat suspension, and floor of the forklifts. In addition, the energy transmissibility of the vibration relative to the frequency domain was evaluated to understand the difference in vibration magnitude (the amount of energy that is transferred) through the measurement chain of the forklift seats. The transmissibility values represent the ratio of the PSDs measured between two measurement locations, where values greater than 1 indicate the amplification, and values less than 1 indicate the attenuation of the vibration exposure by seat cushion or seat suspension.

4.2.6 *Statistical Analysis*

The independent and dependent variables of the current study are as follows:

- Independent variables:

- The components of the forklift seat's (seat suspensions vs. seat cushions)
- Dependent variables:
 - WBV exposures [A(8) and VDV(8)]
 - Time to action limits (TAL)
 - Seat Effective Amplitude Transmissibility (SEAT)
 - Power Spectral Density and Transmissibility ratio

The outcomes of dependent variables in this study were summarized using median and interquartile range values (25th and 75th percentile) due to the small sample size and non-normality of WBV exposures data. Kruskal–Wallis tests were used for statistical analysis by statistical computer software (JMP Version 15; SAS Institute; Cary, NC) to understand whether there was a difference in WBV exposures, TAL, and SEAT values between seat top, top of the seat suspension, and floor measurements. Statistical significance was noted when a p-value was less than 0.05.

4.3 RESULTS

4.3.1 *Comparison of Whole-Body Vibration Exposures between the Forklift Seat Measurement Locations During the Whole Regular Work Shift*

The A(8) ($p = 0.02$) and VDV(8) ($p < 0.01$) vibrations measured at the floor were significantly reduced by the seat suspension (Figure 4.4.). In contrast, the median WBV exposures at the seat top were similar or higher compared to the vibrations measured at the top of the seat suspension. The floor-measured vibrations exceeded both A(8) and VDV(8) E.U. daily vibration action limits (0.5 m/s^2 and $9.1 \text{ m/s}^{1.75}$, respectively), where the A(8) vibrations measured at the top of the seat suspension and seat top were below the action limits. Although seat suspension decreased the floor-measured VDV(8) vibrations below the E.U. daily vibration action limits, the seat cushion amplified the vibration, which exceeded the action limit.

The estimated operating time to reach the action limit (TAL) for A(8) and VDV(8) at the top of the seat suspension showed about a 3-fold and 9-fold increase, respectively, relative to the TAL for the vibrations measured at the forklift floor (Figure 4.5.). However, the seat cushion reduced VDV(8) TAL, relative to the TAL for the vibration levels measured at the top of the suspension.

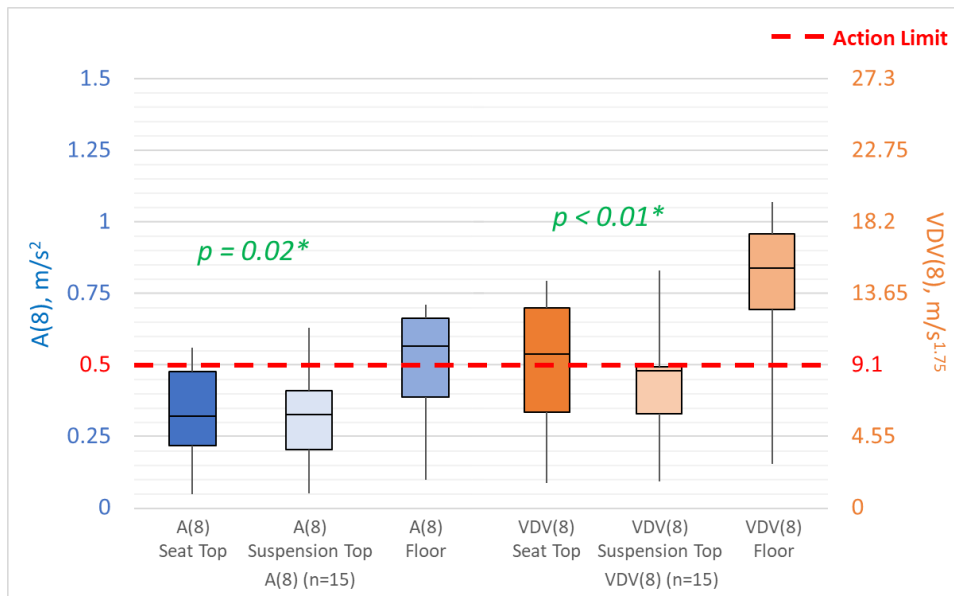


Figure 4.4. $A(8)$ and $VDV(8)$ WBV exposures across the measurement locations of the forklift seat during regular work shift. The red dashed line indicates the European Union's daily vibration action limits. The boxes indicate interquartile ranges; the horizontal line in the boxes are median values; whiskers indicate maximum and minimum values.

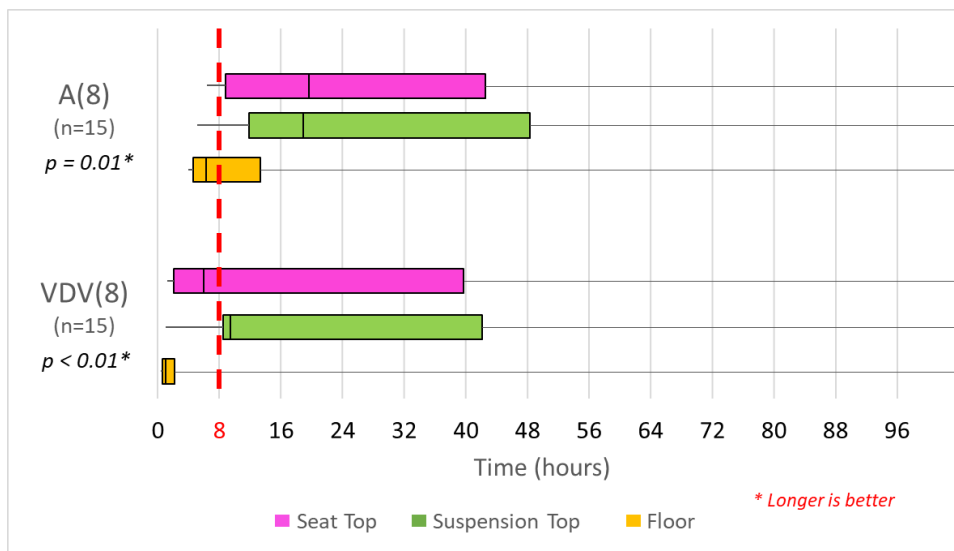


Figure 4.5. Time to action limit (TAL) based on $A(8)$ and $VDV(8)$ WBV exposures measured across the locations of the forklift seat during the regular work shift. The boxes indicate interquartile ranges; the horizontal line in the boxes are median values; whiskers indicate maximum and minimum values.

4.3.2 *Comparison of Whole-Body Vibration Exposures between Forklift seat Measurement Locations when the Forklifts were Actively Moving During the Regular Work Shift*

Both A(8) and VDV(8) WBV exposures at the top of the suspension were significantly lower compared to the floor-measured vibration levels ($p < 0.01$ and $p = 0.01$, respectively) (Figure 4.6.). However, the median A(8) and VDV(8) WBV exposures at the seat top were similar or slightly higher compared to the vibrations measured at the top of the suspension. Floor measured A(8) and VDV(8) vibrations were above the E.U. daily vibration action limits. The seat suspension decreased the floor-measured vibration below the A(8) and VDV(8) action limits, and the seat cushion did not alter (increase or decrease) the WBV exposures relative to the exposures measured at the top of the seat suspension. The estimated TALs based on the vibrations measured at the top of the seat suspension were significantly increased compared to the TALs based on the floor-measured vibrations, by 2.5 and 13 times for the A(8) and VDV(8) exposures, respectively (Figure 4.7.). However, TALs based on the exposures measured at the top of the seat increased about 0.5 hours and 18 hours for A(8) and VDV(8) exposures, respectively. The median SEAT values showed that the seat suspension reduced about 46% of the A(8) and 49% of the VDV(8) floor-measured vibrations (Table 4.2.). The seat cushion attenuated an additional 6% and 4% of the A(8) and VDV(8) WBV exposures that were not attenuated by the seat suspension.

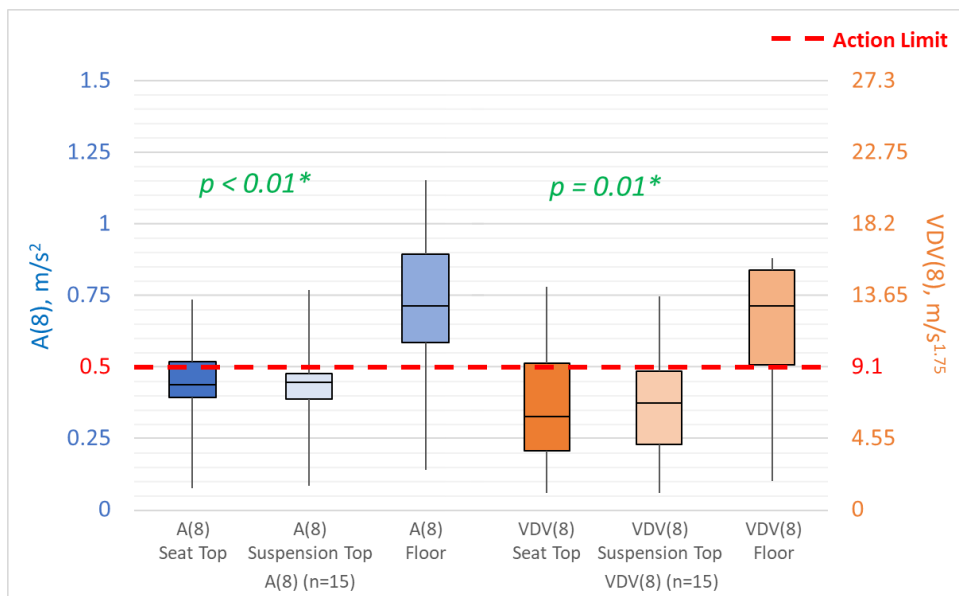


Figure 4.6. A(8) and VDV(8) WBV exposures across the measurement locations of forklift seat based solely on the periods of forklift movement/operation. The red dashed line indicates the European Union's daily vibration action limits. The boxes indicate interquartile ranges; the horizontal line in the boxes are median values; whiskers indicate maximum and minimum values.

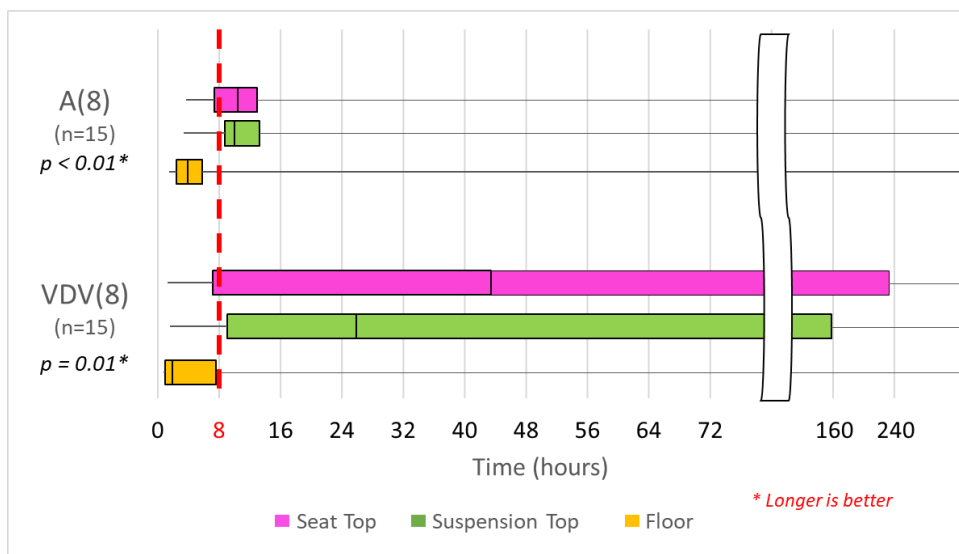


Figure 4.7. Time to action limit (TAL) based on A(8) and VDV(8) WBV exposures measured across the locations of the forklift seat while the forklifts were active during regular work shift. The boxes indicate interquartile ranges; the horizontal line in the boxes are median values; whiskers indicate maximum and minimum values.

Table 4.6. Comparison of median (25th, 75th) A(8) and VDV(8) regular work shift Seat Effective Amplitude Transmissibility (SEAT) between forklift seat measurement locations based solely on the periods of forklift movement/operation

Parameter	SEAT (IQR) (n = 15)			P-Value
	Seat Top/ Suspension Top	Suspension Top/ Floor	Seat Top/ Floor	
A(8) (%)	92.8% (88.6, 107.5)	54.0% (49.9, 82.2)	56.3% (50.9, 74.7)	< 0.01
VDV(8) (%)	96.3% (90.3, 108.5)	50.9% (44.8, 73.9)	58.6% (41.8, 68.1)	< 0.01

4.3.3 *Whole-Body Vibration Exposure Comparison between Forklift Seat Measurement Location based on the Common Route*

Similar to the data analysis above based on the forklift solely moving, the seat suspension significantly reduced floor measured A(8) and VDV(8) vibrations but were not reduced or altered by the seat cushion (both p-values < 0.01) (Figure 4.8). All vibration measurements at each location were above the A(8) and VDV(8) E.U. daily vibration action limits. The TAL based on the A(8) and VDV(8) exposures measured at the seat suspension was extended by 3 to 6-folds relative to the TAL of the floor measured vibrations (Figure 4.9.). However, TALs based on the measurements at the top of the seat was reduced about 0.5 hours, due to the seat cushion amplifying WBV exposures relative to vibration measured at the top of the seat suspension. The median SEAT values showed that about 42% and 45% of the A(8) and VDV(8) exposures, respectively, were attenuated by the seat suspension relative to the floor-measured vibrations (Table 4.3.). Nevertheless, the seat cushion only attenuated about 6% and 10% of A(8) and VDV(8) exposures that were transmitted from the top of the seat suspension.

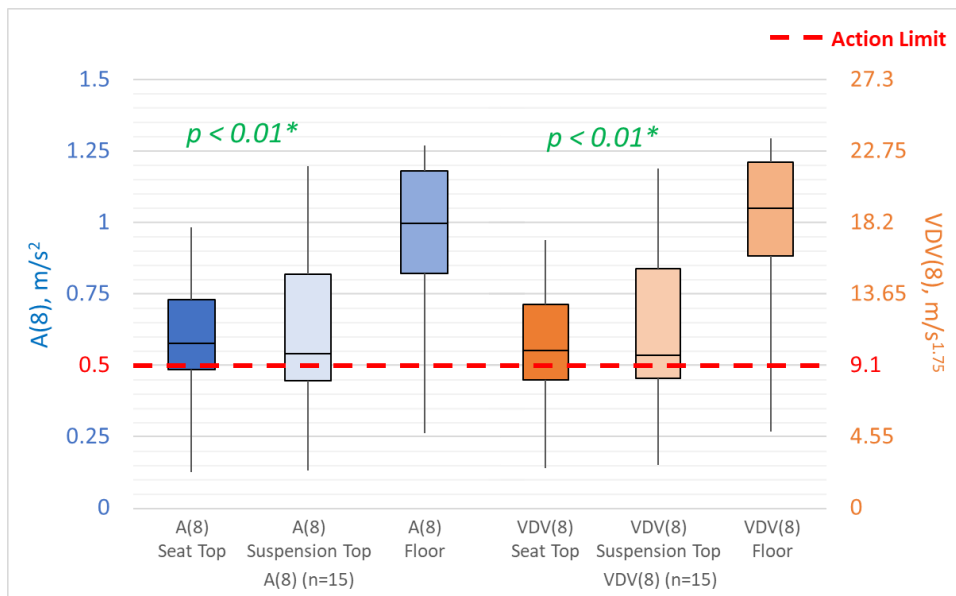


Figure 4.8. A(8) and VDV(8) exposures across the measurement locations of forklift seat while the forklifts were going over the common route. The red dashed line indicates the European Union's daily vibration action limits. The boxes indicate interquartile ranges; the horizontal line in the boxes are median values; whiskers indicate maximum and minimum values.

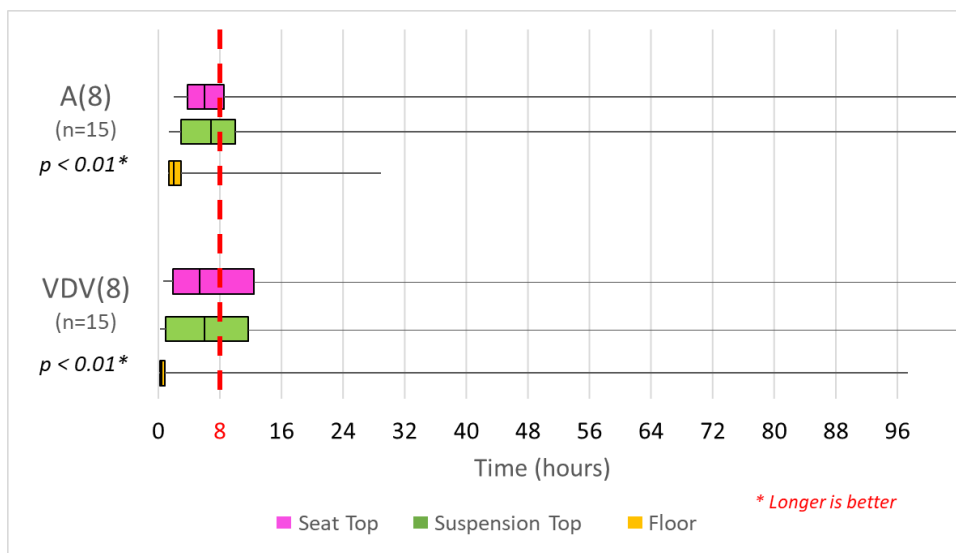


Figure 4.9. Time to action limit (TAL) based on A(8) and VDV(8) measured across the locations of the forklift seat, while the forklifts were operated over the common route. The boxes indicate interquartile ranges; the horizontal line in the boxes are median values; whiskers indicate maximum and minimum values.

Table 4.7. Comparison of median (25th, 75th) A(8) and VDV(8) Seat Effective Amplitude Transmissibility (SEAT) between forklift seat measurement locations, when traveling over the common route

Parameter	SEAT (IQR) (n = 15)			P-Value
	Seat Top/ Suspension Top	Suspension Top/ Floor	Seat Top/ Floor	
A(8) (%)	93.7% (85.4, 110.3)	58.1% (46.2, 90.5)	58.2% (49.6, 77.7)	< 0.01
VDV(8) (%)	89.8% (83.6, 101.7)	54.7% (44.8, 85.5)	52.0% (44.8, 69.6)	< 0.01

4.3.4 Comparison of Whole-Body Vibration Exposure by the Operator's Body Mass

Vibration exposures at the floor, top of the suspension, and top of the seat were further compared relative to the body mass of the forklift operators (Figure 4.10.). The study results identified that the seat suspension attenuated almost all the floor-measured vibration for the heaviest drivers and moderate amount for the medium body mass operators. However, the seat suspension only attenuated a very small amount of floor-measured vibration with the lighter operators. With regards to the seat top measurements, the mass-dependent trend in seat cushion performance was opposite to the seat suspension performance; as the forklift operators' body mass decreased, the seat cushion provided more vibration attenuation.

This trend in vibration patterns was also shown in the SEAT results. The SEAT values between the floor and the top of the seat suspension showed the lowest value with heavier forklift operators, and the value increased as the body mass of the operators decreased. The SEAT values between the seat top and top of the seat suspension showed the lowest value with lighter forklift operator groups and increased as the body mass of the operators increased. Both A(8) and VDV(8) WBV exposures showed similar results based on the operators' body mass change.

Table 4.8. Median (25th, 75th) A(8) and VDV(8) vibration exposures measurement and SEAT values between locations of the forklift seat relative to the body mass of the forklift operators over the common route data.

Parameter	Measurement locations	Median (IQR)			P-Value
		Light (n=4) < 95 kg	Medium (n=3) 95 – 113 kg	Heavy (n=3) > 113 kg	
A(8) (m/s ²)	Seat top	0.88 (0.55, 0.98)	0.48 (0.42, 0.62)	0.55 (0.54, 0.65)	0.24
	Suspension Top	1.02 (0.57, 1.16)	0.52 (0.51, 0.72)	0.52 (0.49, 0.57)	0.41
	Floor	1.04 (0.90, 1.21)	1.08 (1.06, 1.17)	1.02 (0.96, 1.25)	0.79
A(8) SEAT (%)	Seat Top / Suspension Top	86.7 (85.3, 101.3)	90.9 (81.6, 91.0)	110.9 (107.7, 114.6)	0.06
	Suspension Top / Floor	86.9 (56.0, 108.7)	51.2 (42.9, 61.5)	46.5 (44.8, 60.8)	0.15
VDV(8) (m/s ^{1.75})	Seat top	15.0 (9.3, 16.9)	8.4 (7.8, 10.1)	9.6 (9.0, 10.6)	0.24
	Suspension Top	18.1 (10.3, 21.3)	9.1 (9.0, 12.5)	9.4 (9.1, 10.2)	0.41
	Floor	20.0 (17.3, 22.2)	21.7 (21.1, 22.7)	18.9 (17.2, 23.0)	0.55
VDV(8) SEAT (%)	Seat Top / Suspension Top	84.1 (83.2, 89.3)	87.0 (77.0, 90.0)	100.7 (99.8, 105.9)	0.06
	Suspension Top / Floor	83.9 (54.2, 106.2)	48.2 (40.7, 59.8)	45.7 (42.8, 58.8)	0.10

4.3.5 Power Spectral Densities of Whole-Body Vibration Exposure at the Forklift Floor, Top of the Suspension, and Seat Top

Power Spectral Densities (PSDs) results based on the vibrations measured at the floor of the forklifts showed that the majority of the vibration energy was centered at 5 Hz (Figure 4.11.). Also, the vibration measured at the floor had a second energy peak at 10.5 Hz. Compared to the 5 Hz vibration energy measured at the floor, the vibration energy measured at the top of the seat suspension was about five times lower. The seat suspension appeared to attenuate the majority of the vibration energy across the frequency range, and the seat cushion appears to amplify the remaining vibration energy coming up through the seat suspension between 2.0 – 5.5 Hz.

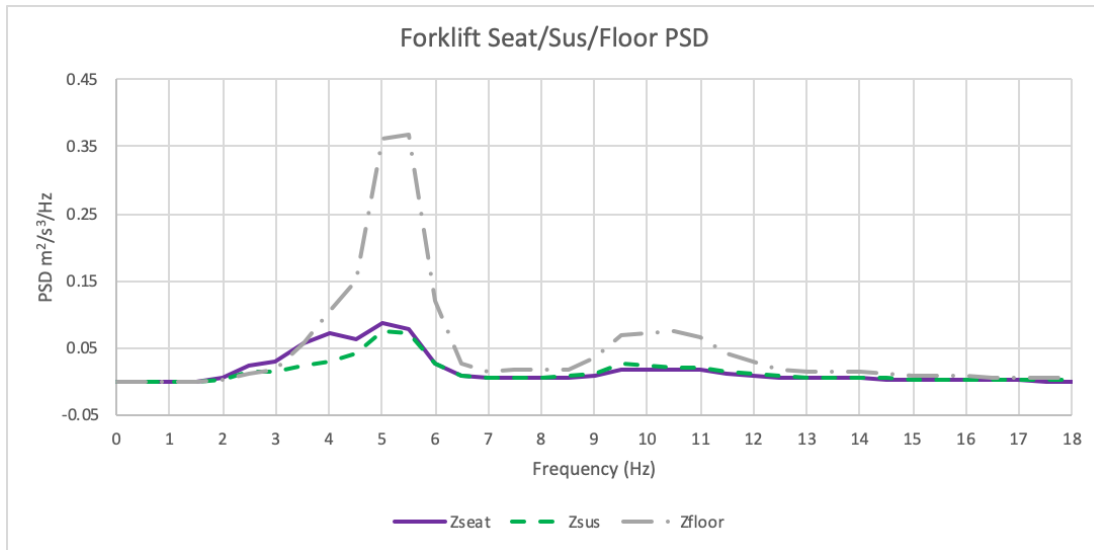


Figure 4.10. The median weighted Power Spectral Densities of the vibration measured at the floor, top of the seat suspension, and seat top, based on the forklift operating over the common route.

4.3.6 Transmissibility of the Forklift Whole-Body Vibration Exposure

The transmissibility values (the ratio of the PSDs) based on the vibration measured at the floor and top of the seat suspension (dashed green line) showed that seat suspension predominantly attenuated the floor transmitted vibration at 3 Hz and above (Figure 4.12.). In contrast, the transmissibility value between the seat top and top of the seat suspension (solid pink line) showed that the seat cushion amplified the vibration coming from the suspension top at frequencies of 5 Hz and below. Based on the measurements at the floor and seat top, which included the combined performance of the seat suspension and seat cushion, the forklift seat (dash-dot gray line) amplified the vibration energy below 3.5Hz due to poor performance by the seat suspension and amplification by the foam, and substantially attenuated the vibration at 5 Hz and above due to the combined synergistic efforts of the suspension and cushion.

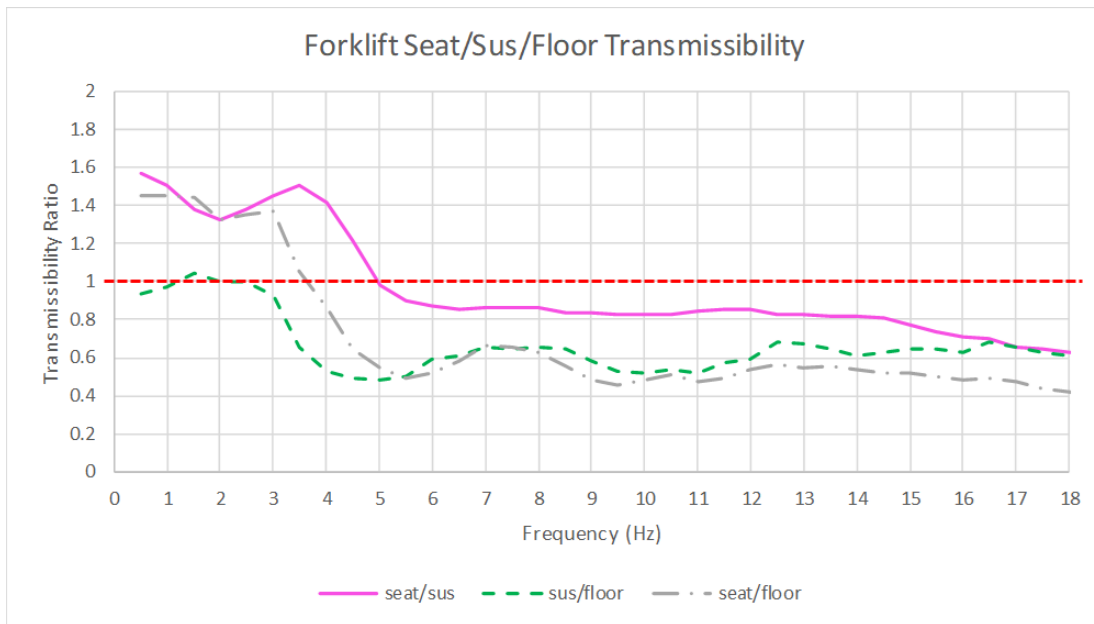


Figure 4.11. Transmissibility of the WBV exposures across the forklift seat (seat suspension to seat top, floor to seat suspension, and floor to seat top) measured while the forklifts were operated over the common route.

4.4 DISCUSSION

4.4.1 *Summary of Key Findings*

The purpose of this study was to evaluate the attenuation performance of a representative and commercially available forklift seat and quantify the relative contribution of the seat suspension and cushion in reducing WBV during regular forklift operation in a real field setting. Vibrations were measured at three levels (i.e., floor, suspension top, and seat top) to compare the performance of the seat suspension and seat cushion in reducing forklift-generated vibration exposures. In general, the results showed that the mechanical seat suspension used in this study significantly (up to 49 %) reduced the forklift-generated vibrations measured at the floor while the seat cushion had little to no effect in reducing the WBV exposures. These differences were dependent on WBV parameters [A(8) or VDV(8)]. Moreover, while the seat suspension played a greater role in reducing WBV (23-53% reduction relative to the floor measured vibration) compared to the cushion, the relative contribution of the seat suspension and cushion was significantly affected by the body mass of the forklift operators.

4.4.2 *Differences in the Seat Suspension and Seat Cushion Performance on Attenuating Forklift-Generated Vibration*

The results showed that the seat suspension significantly contributed to attenuating floor-measured vibration (between 42% to 49%) while a relatively small contribution from the seat cushion was found. These attenuation results were relatively consistent with the attenuation properties of the mechanical seats studied by Blood et al. (2010) (i.e., 45% and 35% attenuation for A(8) and VDV(8) measures, respectively). The PSDs analysis further proved the greater contribution of the seat suspension in attenuating the vibration as the seat suspension attenuated

about 80% of the peak floor-measured vibration energy at 5.5 Hz (Figure 4.10.). Moreover, the seat suspension attenuated the vibration over a wider frequency range (3 Hz and above) compared to the seat cushion (5 Hz and above). These vibration attenuation frequency range of the seat suspension and seat cushion overlaps to the resonate frequency of the human spine (4 – 12 Hz) (Ryan, 2018), which indicates that the performance of the forklift seat component may contribute on reducing the risk of spine degeneration, especially with significant attenuation by the seat suspension at 5.5 Hz.

The frequency range over which the seat suspension attenuated the floor-measured vibration in this study was consistent with previous studies showing that typical mechanical suspension seats reduced WBV starting from 2 Hz and above (Donati, 2002). Also, the frequency range at which the seat cushion attenuated the vibration in the current study matched the findings of a previous study by Khaksar et al. (2013). As a result, the overall findings of the current study provided further evidence for the significant role of seat suspension on reducing the forklift operators' exposure to WBV.

4.4.3 *Performance of the Seat Suspension and Seat Cushion Performance based on the Operator's Body Mass*

Although this study showed that the seat suspension had a greater contribution to WBV reduction compared to the seat cushion, the relative contribution of the seat suspension and seat cushion in reducing WBV was highly dependent on the body mass of the forklift operators. For forklift operators with medium (95- 113 kg) and heavy body mass (113 kg and higher), the seat suspension significantly attenuated 49-54 % of the floor-measured vibrations while the seat cushion did not attenuate much or even amplified up to 10%. In contrast, the relative contribution of the seat suspension and cushion were similar for the lighter forklift operators.

The performance difference of the seat suspension and seat cushion relative to the body mass were due to the systematic mechanisms of each forklift seat component. For example, when the seat cushion is compressed by a heavier operator, the stiffness of foam increases to a point where its ability to attenuate vibration is decreased (Ahmadian et al., 2002). In contrast, as lighter operators do not fully compress the seat cushion, the foam has a greater degree of compressive performance remaining and can attenuate a greater degree of exposure to WBV (Ahmadian et al., 2002). Moreover, the stiffness of the typical seat suspension, which determines the displacement of the suspensions' vertical travel and prevents bottom-out effect, is set for heavier forklift operators with high stiffness. Hence, the suspension stiffness may have been relatively high enough to create the sub-optimal suspension displacement, and therefore may not have the same extent of the vibration damping effect with the heavier operators (Donati, 2002; Heidarian & Wang, 2019).

The current study's findings are consistent with previous studies that have found an association between driver body mass and the degree of WBV exposures experienced by forklift operators. A study by Blood et al. (2010), which compared the WBV exposures of the mechanical suspension seat by three forklift operators body mass groups, also showed an inverse trend of WBV exposures relative to the body mass of the forklift operators. Mayton et al. (2006) also emphasized that the forklift driver's exposure to WBV was heavily mass-dependent, wherein the WBV attenuation and the body mass of the driver were inversely related. A similar result was shown by Motmans (2012), in which the study also found that the mechanical suspension seat was more effective for heavy operators compared to the air suspension seat.

4.4.4 *Methodological Advances of the Current Study*

The method of the current study to evaluate the performance of the seat suspension and seat cushion in reducing WBV exposures was unique and improved upon previous methodologies, which only measured the vibration exposures at the forklift seat and floor. Previous lab-based studies have demonstrated the importance of making measurements at different locations on the seat, as the seat suspension and seat cushion performs differently on attenuating vibration (Heidarian & Wang, 2019; Alan G. Mayton et al., 2006). However, field-based studies have typically not collected measurements from the multiple levels, which comprise the seat suspension. For example, the study by Blood et al. (2010) focused on comparing the WBV exposures measured at the top of air suspension and mechanical suspension seat relative to the vibrations measured at the floor. Likewise, Joubert (2005) compared the performance of two forklift seats with and without suspension by measuring WBV exposures at the seat top and floor. Also, a study by Motmans (2012) compared the WBV exposures of two different suspended forklift seats based on the seat top measurements but not measuring floor vibrations. These previous studies evaluated the performance of the forklift seat considered only the difference between the WBV exposures measured at the seat top and the floor, rather than examining the performance of the seat suspension and seat cushion individually.

In the current study of adding vibration measurement at the top of the seat suspension, presented the evidence for understanding the individual contribution by the seat suspension and seat cushion to overall forklift seat performance on reducing the vibration exposures originating from the forklift floor. Because the mechanical suspension seat has moving parts, such as spring blades and shock absorbers, which allow for greater travel, it has more ability to dampen undesired vibration compared to the seat cushion alone (Heidarian & Wang, 2019). Also, Mehta & Tewari

(2010) found that different foam compositions used in the seat cushions can influence WBV transmission. Therefore, by the understanding of vibration reduction by each forklift seat component and the potential component associations and interactions, more efficient and strategic component solutions may be specified to protect forklift operators from WBV exposures better.

Despite the significant contribution of the seat suspension on reducing the majority of the forklift seat vibration exposures, there are some potential factors that may merit further consideration, and these factors highlight the benefit of understanding the ability of the seat suspension and seat cushion to work together and individually. A study by Donati (2002) suggested that the seat suspension resonant frequency needs to be considered relative to the road condition where the forklifts are operated, as the seat suspension may amplify the WBV when the exposed vibration frequency is less than its resonant frequency. Rebelle (2000) mentioned that seat suspension requires a sufficient length of travel to prevent bottoming or topping due to the impulsive WBV exposures by shocks, bumps, and jolts. Additionally, attenuation from seat cushions is highly influenced by the composition of the foam used in the seat cushion (Mehta & Tewari, 2010), where it has been found that polyurethane foam seat cushions improved seat comfort, but only for a short duration (40 minutes) (Mansfield, Sammonds, & Nguyen, 2015). These findings suggest that identifying the performance of each seat component may benefit from providing further knowledge of reducing WBV exposures to operators.

4.4.5 *Study Limitation*

Although this study identified the significant influence of the seat suspension of attenuating the forklift-generated vibrations that transmit through the forklift seat, the present study has some noteworthy limitations. First, due to the small sample size, the study results may not sufficiently provide the generalizability of the forklift mechanical seat suspension and seat cushion

performance during the regular work shift. Despite the limitation, this study was able to identify some significant differences in performance toward vibration attenuation between seat suspension and seat cushion accounting for real forklift operating conditions. Also, similar demographics of the forklift operators, such as similar BMI, to the previous studies (Blood et al., 2010; Deshmukh, 2009; Hoy et al., 2005), may provide some additional generalizability that this study results can be referred in other industries.

Second, there may be some measurement errors as the height of the seat suspensions were not controlled. The lack of controlling the seat suspension height relative to the forklift operators' body mass may have generated negative influences on the vibration measurements (i.e., seat bottom-out effect). As a result, this limitation may have contributed to small differences in vibration attenuation between medium and heavy body mass. However, our study was able to differentiate the seat suspension performance relative to the forklift operators' body mass.

4.5 CONCLUSION

This study demonstrated that the mechanical seat suspension had a greater contribution to reducing WBV in forklift operation compared to a seat cushion. However, the relative contributions of the seat suspension and cushion were significantly dependent on the operators' body mass. The study results may provide valuable information to forklift operators and their managers for developing an effective intervention (e.g., engineering and administrative controls) to reduce WBV exposure and therefore improve the health and safety of the forklift operators.

Chapter 5. CONCLUSION

5.1 DISSERTATION SUMMARY

The primary purpose of this dissertation was to characterize the WBV exposures experienced by the forklift operators using their existing forklifts during their regular work shifts and to seek possible solutions to reduce the exposures. The main findings from this dissertation are summarized as follows:

Chapter 2 of this dissertation compared the WBV exposures between the forklifts with and without the mast-based vibration damping system. The study identified that operators of forklifts with mast-based vibration damping systems experienced lower WBV exposures for both continuous average vibration exposures [A(8)], and cumulative impulsive vibration exposures [VDV(8)] compared to those operators who operated forklifts without the damping system. Despite the lack of statistical significance, the study showed that self-reported pain levels paralleled the WBV exposures and were relatively lower for those who operated the forklifts with the mast-based vibration damping system compared to those operating the other forklifts without the mast-based vibration damping system.

Chapter 3 compared the performance of two common types of forklift tires—solid tires and air-filled pneumatic tires—in reducing forklift operators' exposure to WBV. Using identical model forklifts at two different study sites, his study showed that the pneumatic tire forklift operators experienced higher WBV exposures compared to the solid tire forklift operators. Similar to the findings in Chapter 2, the operators who experienced lower WBV exposures (solid tire forklift operators) reported lower musculoskeletal pain levels than those exposed to higher WBV (pneumatic tire forklift operators). However, these differences in musculoskeletal pain between the tires were small and did not reach statistical significance.

Chapter 4 characterized the transmission of vibrations from floor to the seat suspension top to the cushion to determine the relative contribution of the seat suspension and seat cushion in reducing overall WBV exposures during actual field forklift operations. The study results indicated that, over all subjects, the seat suspension was the main contributor to reducing forklift-generated vibration compared to the seat cushion. However, the study also found that the contribution of the seat suspension and cushion depended on the body mass of the forklift operators. For the heavy forklift operators with a body mass of 113 kg or higher, the majority of the forklift-generated vibration was attenuated by the seat suspension with little to no additional attenuation from the seat cushion. In contrast, for the lighter forklift operators (body mass ≤ 95 kg), the seat cushion was predominantly responsible for attenuating the WBV exposures, and the seat suspension had a lesser role in vibration attenuation.

5.2 STUDY CONTRIBUTIONS

The current dissertation expanded the understanding of the factors that contribute to reducing WBV exposures experienced by forklift operators. To reduce WBV exposures, previous studies have extensively studied the effects of load capacity, engine types, and road conditions (Deshmukh, 2009; Joubert, 2002a; Motmans, 2012) in altering the WBV exposures experienced by forklift operators. In addition, in a similar line of research relevant to Chapter 2, Cvetanović et al. (2013) showed that the design and structure of the forklifts (suspended chassis and cabin) could have a significant impact on WBV. However, in actual working environments, the present study evaluated the structural effectiveness of the mast-based vibration damping system in reducing forklift operator WBV exposures. The results showed that the mast-based vibration damping system effectively reduced the forklift operators' exposure to WBV. The benefits of the vibration

damping system identified in this study provide important information to the forklift manufacturers and procurement parties to protect forklift operators from WBV exposures.

This dissertation utilized different approaches to evaluate the most realistic WBV exposures the operators experience in their actual day-to-day operations that are influenced by the forklift tires. The differences in WBV between the pneumatic- and solid-tire types have been previously identified (Lemerle & Mistrot, 2001; Malchaire et al., 1996). However, these studies were conducted in highly controlled settings (Malchaire et al., 1996; Zucco & Gomes, 2009), which may not generalize the real forklift operation settings the operators may encounter during their typical regular work shift. The current study compared WBV exposures between the forklifts with pneumatic and solid tires during the regular work shift, accounting for all operating conditions the operators encountered. This approach provided more representative information on the forklift tire performance in mitigating WBV exposures.

Furthermore, this dissertation also employed an innovative approach where the vibration exposures were evaluated at the floor, suspension top, and seat top in order to better understand how the contribution of the various seat components in altering or attenuating the vibrations being transmitted up from the forklift floor. Although previous studies have quantified the relative importance of the seat suspension and cushion in attenuating WBV (Ahmadian et al., 2002; Heidarian & Wang, 2019), these studies were conducted in a highly controlled environment; and therefore, the result of these studies may not be representative or generalizable to real forklift operation. The current study is one of the first studies to evaluate the relative contribution of the seat suspension and seat cushion in reducing a forklift operator's overall vibration exposures during their actual work. The study identified that the contribution of vibration attenuation by the suspension and cushion depended on the body mass of the forklift operators. These weight

dependent behaviors and differential attenuation by the seat suspension and seat foam may provide seat manufacturers with new ways of design seats in order to better pair suspension and foam performance and may provide important practical implications and recommendations in selecting adequate seats based on the demographics of an organizations' forklift operators.

5.3 STUDY IMPLICATIONS

Using both real work and controlled measurements, this dissertation further characterized forklift design elements, which can alter WBV exposures and increased the knowledge on how these various design elements affect the WBV exposures experienced by the forklift operators. Companies that employ forklift operators may use the findings of this dissertation to purchase forklifts and specify the appropriate tires and seats to best match their operating environment in order to reduce their forklift operator WBV exposures. Administratively, managers may be able to manage the WBV exposures rotating their operators across higher exposure tasks to reduce their operator's chances of exceeding the EU daily vibration action limits. Also, by purchasing seats, such as air-ride seats, which are better able to handle a range of body weights, or by training the operators to adjust the forklift seat according to their weight, this may help reduce forklift operator WBV exposures.

Although purchasing forklifts with new and improved engineering designs and componentry may provide greater capability for further reducing forklift operator WBV exposures, these purchases may be an incremental and additional expense that has to be weighed against the potential savings in injuries, claims costs, lost productivity and forklift operator health and well-being. This dissertation identified that WBV exposures could be reduced and cost savings may result by the selection and purchase of forklifts with mast-based vibration dampening systems, the correct selection of forklift tires to match the operating environment and conditions, and either the

purchase of seats that minimize weight-dependent performance or ensuring that forklift operators know how to correctly adjust their seats. By optimizing components like tires and seats on forklifts that employers already possess, any incremental costs and purchases may be outweighed by the savings achieved through reduced claims costs, improved productivity, and improved forklift operator health and well-being.

5.4 STUDY LIMITATIONS

Although this study tried to minimize limitations, several limitations were unavoidable, as described throughout the chapters. One of the main limitations affecting this study was the small sample size due to the limited number of the forklift operators employed at the manufacturing sites and the reluctance of some forklift operators to volunteer and participate in the study. The small sample could have resulted in a lack of statistical power, which could influence the differences or the lack thereof in differences in WBV exposure and/or the self-reported pain levels between the conditions evaluated. Despite the small sample size, which may limit the generalizability, many of the study results were comparable to previous forklift WBV exposure studies.

In addition to the small sample size, the short duration (around 4 hours) over which the forklift operators' musculoskeletal pain levels were measured may not have been sufficiently long enough to identify the true daily changes in pain due to forklift operation. As mentioned in Chapter 2, previous studies have monitored the musculoskeletal pain level changes over longer durations with larger sample sizes compared to this study (Gopanna et al., 2015; Hoy et al., 2005). The lack of statistical significance with the small sample size and short-term pain assessments may have limited the capability to measure and detect changes and differences in pain between the various conditions evaluated.

Furthermore, the aim of the studies in this dissertation was designed to identify the specific contribution of each forklift factors (vibration damping system, forklift tires, and forklift seat components) for reducing forklift operator WBV exposures. However, remaining uncontrolled measurement variables, including different operating tasks assigned to each forklift operator, forklift operating styles by each operator, and condition of each forklift used in the studies may have limited estimating of the vibration damping effect solely by each forklift factor discussed in the dissertation.

5.5 FUTURE RESEARCH

Recognizing the extensive usage of forklift trucks in various industries, as well as the diverse types of available equipment and working environments, further refining the characterization of the WBV exposures experienced by forklift operators during their regular work is essential. Future work may leverage off the findings of this dissertation by evaluating the WBV exposures differences studied in this dissertation with larger sample sizes and full-day or multi-day assessment of musculoskeletal discomfort associated with forklift operation. With an increase in sample size and duration of monitoring discomfort associated with forklift operation, future studies may look at the comparison of specific manufacturer's vibration-damping features, and whether those features effectively contribute to reducing WBV exposures for the operators. In addition, by further characterizing the specific vibrations that these features are intended to attenuate—such as the frequency energy content of the vibration—we will gain a better understanding of the mechanics of vibration damping, and how the vibration damping may benefit the health of operators.

Future research may also further examine the performance of different seat foam tops utilized in combination with the existing seat suspensions evaluated. Replacing existing seat

cushions with improved seat foams, which are designed to reduce the transmission of vibration more effectively, will cost less than replacing the entire seat. Considering the effects that drivers of different weights had on seat foam performance in both the current and previous studies (Ahmadian et al., 2002), future research may examine the function of the driver seat system as it responds to the body weights of different operators, posture or seating behavior of the forklift operators.

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APPENDIX A (BASELINE SURVEY)

BASELINE SURVEY

Please answer all questions as accurately as possible, and if you prefer not to answer a particular question just tell us

Section 1: Occupational Information

1. How long have you worked at this company? _____ Years _____ Months
2. What are your regular job responsibilities? _____
3. What is your normal work shift? (check and write start and end time)
 - 1st shift (early morning to evening): _____
 - 2nd shift (afternoon to late night): _____
 - 3rd shift (late evening to early morning): _____
 - Other: _____

Section 2: Forklift and Operation

1. What is the number of the forklift you operate most often? _____
2. What is the model name of the forklift you often operate? _____
3. What is the current setting of the tires on the forklift you often operate?
 - All solid tires
 - All pneumatic tires
 - Front solid tires, rear pneumatic tires
 - Front pneumatic tires, rear solid tires

4. Approximately, how much do you perform following tasks during your normal work hours (in percentages)?

- i. Driving (Outdoor) _____ %
- ii. Driving (Indoor) _____ %
- iii. Loading / Unloading _____ %
- iv. Lifting _____ %
- v. Hauling _____ %
- vi. Others (Please specify) _____ %
- vii. Others (Please specify) _____ %
- viii. Others (Please specify) _____ %

5. Based on your experience, rank the order of following forklift operating tasks from easiest to hardest

- Driving (outdoor) _____
- Driving (indoor) _____
- Loading _____
- Unloading _____
- Lifting _____
- Hauling _____
- Others (Please specify) _____
- Others (Please specify) _____
- Others (Please specify) _____

6. Based on your experience, how would you rate the riding experience of your current forklift tires (Answer one with appropriate tire setting)

1) All Solid tires

Excellent Experience										Worst Experience
0	1	2	3	4	5	6	7	8	9	

2) All Pneumatic tires

Excellent Experience										Worst Experience
0	1	2	3	4	5	6	7	8	9	

3) Front solid tires, rear pneumatic tires

Excellent Experience										Worst Experience
0	1	2	3	4	5	6	7	8	9	

4) Front pneumatic tires, rear solid tires

Excellent Experience										Worst Experience
0	1	2	3	4	5	6	7	8	9	

7. In the past 1 year, did you have any accidents while operating the forklift?

No

Yes

8. While operating your forklift, do you experience discomfort from vehicle-related vibration or vehicle-related shocks/jolts?

No

Yes

9. In average, how many times do you get off from your forklift in one hour during a normal work day? _____ times

10. How many breaks do you take during a normal day? _____ times

11. In average, how long is each break ? _____ minutes

12. Check off what you normally do during your breaks (select all that apply):

Napping

Walking

Eating

Stretching

Drink coffee/tea/energy drink/soda

Doing other work

Maintenance

Doing paperwork

Listening to music

Just relaxing

Using phone

Other, please describe: _____

Section 3: Personal information

1. What is your Age: _____ or What year were you born: _____

2. What is your gender (Check one): Male _____ Female _____

3. What is your height: _____ ft _____ in

4. What is your weight: _____ lbs

5. Do you participate in any form of regular sports exercise (for example, walking, jogging, bicycle riding, aerobics, team sports, also including yard work)?

- I do not participate in any form of regular sports or exercise
- I exercise less than once per month
- I exercise at least once a month but less than one week
- I exercise once or twice per week
- I exercise three or more times per week

Section 4: Health Questions:

This question is about any pain you feel **AT THIS TIME** in your body.

For the following parts of your body, **AT THIS TIME** how would you rate the pain you feel?

Give me a number between 0 and 10, where “0” is no pain, and **9 is the worse pain you can imagine**

Body Parts	No Pain										Worst pain you can imagine									
	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
Shoulder	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
Wrist(s) / Forearm(s)	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
Knee(s)	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
Ankle(s) / Feet	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
Neck	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
Upper Back	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
Lower Back	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
Buttocks / Legs	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9

APPENDIX B (SELF-REPORTED PAIN LEVEL QUESTIONNAIRES)

Section 1. Forklift Tire Satisfaction:

1) The forklift tires I just used provided a comfortable ride.

Strongly
Agree

Strongly
Disagree

1

2

3

4

5

6

7

2) The forklift tires I just used did a good job absorbing vibration.

Strongly
Agree

Strongly
Disagree

1

2

3

4

5

6

7

3) The amount relative motion and stability of the forklift with the tires I just used was acceptable.

Strongly
Agree

Strongly
Disagree

1

2

3

4

5

6

7

Section 2: Health Questions:

This question is about any pain you feel **AT THIS TIME** in your body.

For the following parts of your body, **AT THIS TIME** how would you rate the pain you feel?

Give me a number between 0 and 10, where **“0”** is no pain, and **10 is the worse pain you can imagine**

Body Parts	No Pain										Worst pain you can imagine
	0	1	2	3	4	5	6	7	8	9	
Shoulder	0	1	2	3	4	5	6	7	8	9	10
Wrist(s) / Forearm(s)	0	1	2	3	4	5	6	7	8	9	10
Knee(s)	0	1	2	3	4	5	6	7	8	9	10
Ankle(s) / Feet	0	1	2	3	4	5	6	7	8	9	10
Neck	0	1	2	3	4	5	6	7	8	9	10
Upper Back	0	1	2	3	4	5	6	7	8	9	10
Lower Back	0	1	2	3	4	5	6	7	8	9	10
Buttocks / Legs	0	1	2	3	4	5	6	7	8	9	10

Additional Comments about operating this forklift with these tires.
