Modeling Predictors of Whole Body Vibration Exposure among Saskatchewan Farmers: A Key Step in Low Back Disorder Prevention

A Thesis Submitted to the College of
Graduate Studies and Research
In Partial Fulfillment of the Requirements
For the Degree of Master of Science
In the Department of Community Health and Epidemiology
University of Saskatchewan
Saskatoon

By

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Abstract

Background

Farmers experience a high rate of low back pain (LBP), with a lifetime prevalence of up to 75%. Whole body vibration exposure has been recognized as a significant physical risk factor associated with LBP. The agriculture sector has high whole body vibration exposures related to various machine types; however, little research has assessed vibration exposure in farming due to the inconvenience and cost of direct data collection. Prediction modelling is potentially a cost-efficient way to estimate directly measured exposure.

Objectives

The objectives of this study are to 1) measure the physical exposure of whole body vibration in Saskatchewan farmers and understand its magnitude and variability between farm machinery; and 2) use farm, vehicle, and task characteristics to determine any predictive relationship with directly-measured whole body vibration exposures among Saskatchewan farmers.

Methods

A 1-year field study with 3 repeated farm visits was conducted for whole body vibration measurements on 21 farms within a 400 km distance of Saskatoon. Whole body vibration was assessed using a tri-axial accelerometer embedded in a standard rubber seat pad according to international standards (ISO 2631-1). Whole body vibration data were summarized by machinery type into standardized metrics of root-mean-squared accelerations (RMS), peak, crest factor, and vibration dose value (VDV). Vehicle characteristics were gathered by on-site observations supplemented by open access vehicle descriptions through manufacturers. Farm characteristics and farmer’s self-reported whole body vibration exposure were collected via questionnaires. A manually stepwise method was conducted to build mixed-effects models for both RMS and VDV outcomes.

Results

A total of 87 whole body vibration measurements were gathered from 8 machine types: tractor, combine, pickup truck, grain truck, sprayer, swather, all-terrain vehicle, and skid steer. The average measurement duration was 85 minutes. The mean vector sums were RMS 0.78 m/s^2, peak 19.34 m/s^2, crest factor 27.64, and VDV 10.02 $m/s^{1.75}$. The fixed effects of ‘horsepower’, ‘vehicle transmission type’, ‘farm size’, and ‘farm commodity’ explained 44% of the variance in RMS; while ‘horsepower’, ‘seat suspension type’, ‘loading frequency’, ‘tire tread type’, ‘jerk/jolt frequency’, ‘seat bottom-out frequency’, ‘farm commodity’, and ‘farm size’ explained only 20% of VDV variance.

Conclusion

High mechanical vibration and shocks from a range vehicle types call for action to reduce agricultural whole body vibration. Although VDV is relatively difficult to predict through farm and vehicle features collected in the present study, RMS can be predicted to a moderately useful degree. Predictors identified via modeling can help explain the variances of whole body vibration exposures and may also serve as new surrogates for future whole body vibration exposure assessment.

Acknowledgements

This research was undertaken with support from the Canada Research Chairs program as well as the Saskatchewan Health Research Foundation (SHRF). In the course of my studies, I also received funding support from the Canadian Centre for Health and Safety in Agriculture (CCHSA) through the Founding Chairs Fellowship and the Department of Community Health and Epidemiology through the Devolved Scholarship.

I would like to thank the Saskatchewan Farmers Back Study Team members: Dr. Catherine Trask, Dr. Brenna Bath, Dr. Aaron M Kociolek, and Muhammad Idrees Khan, for the valuable one-year field work experience of Saskatchewan farm visits, spent together. I'm grateful to have worked with such a great and supportive team. I also gratefully acknowledge the generous participation of the farmers and farms involved in the study.

I would like to give my special thanks to my supervisor, Dr. Catherine Trask, for your guidance all the way through my master's studies. You are a delightful soul who always cheer me up whenever I encounter challenges in my studies and life. The professional, curious, patient, humble, and respectful attitude you have towards research taught me key values in becoming an academic person. I appreciate every tiny little thing you have taught me.

I would also like to thank my other committee members: Drs. Stephan Milosavljevic, Niels Koehncke, and Sylvia Abonyi, for your timely feedback, valuable comments, and insightful suggestions. I am grateful to have such great mentors guiding me through this two-year study period.

Dedication

This thesis is dedicated to my dearest parents, Minguang Zeng and Jixiu Liu.

For their unconditional love, support, and encouragement throughout my life.

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List of Abbreviations

ACGIH: American Conference of Governmental Industrial Hygienists
A(8): 8-hour equivalent frequency-weighted acceleration
AIC: Akaike Information Criterion
ATV: All-Terrain Vehicle
BIC: Bayesian Information Criterion
BMI: Body Mass Index
CF: Crest Factor
CI: Confidence Interval
GBD: Global Burden of Disease
GDP: Gross Domestic Product
GEE: Generalized Estimating Equations
GLM: Generalized Linear Model
GNP: Gross National Product
HGCZ: health guidance caution zone
IQR: Interquartile Range
ISO: International Organization for Standardization
LBD: Low Back Disorder
LBP: Low Back Pain
MSD: Musculoskeletal Disorder
OR: Odds Ratio
RMS: Root Mean Square
VDV: Vibration Dose Value
WBV: Whole Body Vibration
YLDs: Years Lived with Disability

Chapter1: Introduction

Low back pain (LBP) is defined as a ‘musculoskeletal disorder affecting the low back’ [1], that includes pain, muscle tension, or stiffness localized below the costal margin and above the inferior gluteal folds, with or without referral to the lower extremities or sciatica [2]. Low back disorder (LBD) is a broader term which includes LBP and refers to a variety of symptoms in the low back region and/or lower extremities which may be due to a range of underlying pathologies such as spinal disc problems, muscle and soft tissue injuries [3].

1.1 Prevalence of LBP

Throughout the world, LBP point prevalence is approximately 12%, and 1-month prevalence is 23%; prevalence rates are increasing with an ageing population [4]. Population-based research has highlighted LBP as a common problem in developed countries. For example, the point, 1-month, and lifetime prevalence of LBP are 21%, 44%, and 63% (respectively) among occupational workers in the United States [5]; 1-month LBP prevalence is about 25% from a national survey in Japan [6]; 1-week and lifetime prevalence LBP are about 34% and 84% (respectively) in Canadian provinces of Alberta and Saskatchewan [7]. In Saskatchewan, it was estimated that 84.1% of adults had experienced LBP through their lifetime in the late 1990s [8].

LBP is also a prevalent condition among working populations, such as nurses, athletes, farmers, and industrial workers, to varying extents. In terms of the LBP lifetime prevalence rate, nurses experience about 75% [9], adolescent athletes encounter about 66% [10], female rowers aged between 14 to16 years old have a rate of 78% and male rowers up to 94% [11]. Agriculture, mining, fishing, forestry, construction, and tradespeople are ranked as LBDs high-risk industrial sectors [12]. In particular, being a farmer presents a substantial risk of musculoskeletal disorders (MSDs) in general [13] and higher risks of chronic low back pain specifically [14]. LBP is the most common MSD among farmers with a lifetime prevalence of 75% and 1-year prevalence of 48% [15].

1.2 Economic burden of LBP

MSDs have become the second major contributor to global YLDs (years lived with disability) while LBP is the predominant cause of YLDs from 1990 to 2010 [16]. In the 1990 Global Burden of Disease (GBD) Study, LBP ranked 11th with a contribution of 58.2 million DALYs (disability-adjusted life years) among all disease burden. Twenty years later, in the latest 2010 GBD study, the DALYs caused by LBP has increased by nearly 40% to 83.0 million; meanwhile, the rank of LBP has climbed to the sixth place [17]. In Canada, LBP is identified as the top five causes of YLDs, along with ‘major depressive disorder', ‘other musculoskeletal disorders’, ‘neck pain’, and ‘drug use disorders’[18].

LBP is a high-cost health problem worldwide. An analysis in Japan indicates that the medical cost of work-related LBP is about 82.14 billion yen in the year 2011[19]. Aside from direct medical expenditures, the larger indirect cost arises from LBP-related productivity losses, including absenteeism (absence from work), presenteeism (attending work despite illness), and disability (long-term permanent inability to perform work) [20]. In Switzerland in 2005, the total cost of LBP was around 8.9 billion euro making up about 2.0% of the gross domestic product (GDP); with up to 60% of those costs associated with indirect medical cost [20]. In the Netherlands, 0.6% of the gross national product (GNP) have been spent on LBP in 2007, which is about 3.5 billion euro; up to 88% are indirect costs [21]. Annually, the United States spends more than 100 billion USD on LBP [22], Canada has an estimated range of 6 to 12 billion CAD for direct LBP medical costs only [23].

1.3 Risk factors of LBDs

LBD is an adverse health outcome resulting from multiple etiological factors. Physical factors, psychosocial factors, and individual factors are three major categories [3]. Physical factors shown to be related to LBD include (1) heavy physical workload [24] (2) lifting and forceful movements [25] (3) awkward/static work postures [26, 27] and (4) whole body vibration (WBV) [28]. Further, research evidence also supports the etiology of an interaction between physical factors in the development of LBDs. In agriculture, the combined effect of occupational exposures when driving different farm equipment, such as trunk rotation and WBV in a seated posture, may play a significant role in LBD's development; however, more occupational exposure assessments are needed [29].

In addition to physical factors, psychosocial factors at the workplace may also be related to LBD. These include: (1) low social support [30] (2) low job satisfaction [30] (3) low job control [31] and (4) high work demands [30, 31]Low social support/low job satisfaction has been studied in a prospective cohort study, with results showing a strong association with LBDs [32].

Aside from physical and psychosocial factors, a variety of individual factors may also have an impact on LBD, including socioeconomic status [22], gender differences [33, 34], older age [35], and genetic background [36].

1.4 Conceptual framework

This proposal borrows from the conceptual framework of the National Research Council Framework (USA) for musculoskeletal disorders (*Figure 1*). This framework will be used to conceptualize physiological pathways from workload to musculoskeletal disorder symptoms. Whole body vibration (WBV) has been highlighted as one significant source of the load which initiates the body's response to it. A main adverse health outcome resulting from WBV exposure is the low back disorder. In order to reduce the impact of LBDs among farmers, a key step is to reduce the exposure to WBV. Modelling WBV patterns in Saskatchewan farmers will help clarify different contributors to WBV and possible interventions to reduce the exposure.

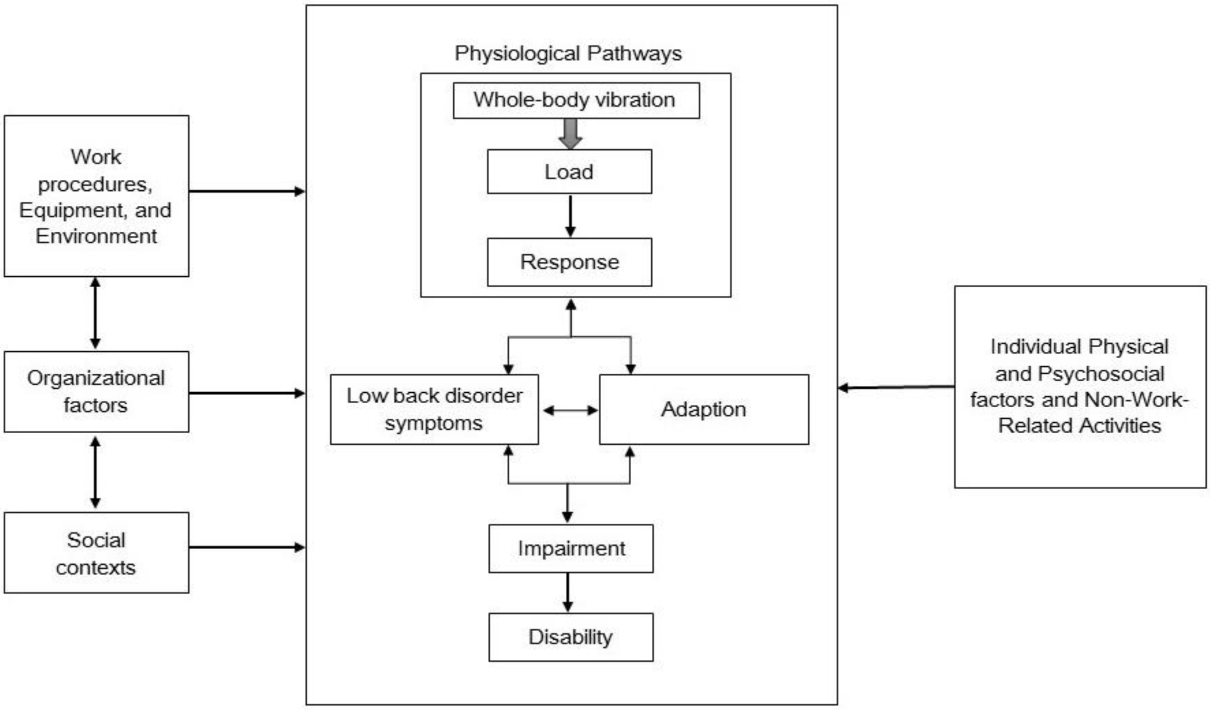

Figure 1. Conceptual framework (adapted from the USA National Research Council Framework for musculoskeletal disorders) [37]

1.5 WBV measurement

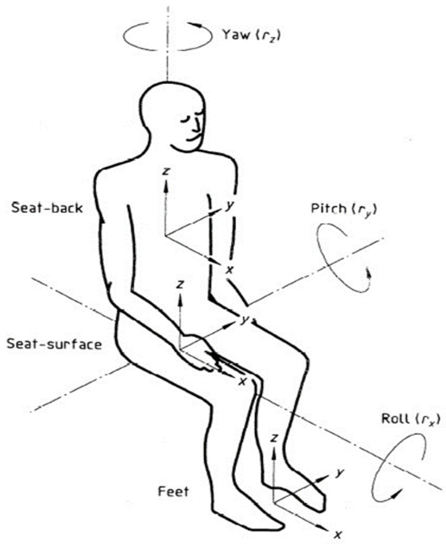

Figure 2. Vibration measured in a seated position[38].

According to the European WBV Good Practice Guide [39], vibration is defined by its amplitude and frequency. The amplitude is generally expressed by acceleration in meters per second per second (m/s^2). The frequency is the number of movements back and forth per second and expressed as a value in cycles per second, or hertz (Hz). ISO 2631-1 [38] has defined WBV measurement methods as well as metrics for analysis. In this method, vibration is measured by vibration transducers; each transducer measures the acceleration from one direction. In order to capture the vibration level on the seat surface completely, a transducer for each axis (X, Y & Z) is needed (*Figure 2*).

For the vibration transmitted from seat to human body, the measurement is obtained on the seat surface. This involves mounting a secured transducer between the surface and the body while trying to ensure that the mount does not change the surface pressure distribution greatly. Vibration level is evaluated by following standardized metrics:

1) The weighted Root-Mean-Square (RMS) acceleration. RMS is the frequency-weighted acceleration expressed in meters per second squared (m/s^2) for the translational vibration [38]. It is calculated by the equation: $a_W = [\frac{1}{T}\int_0^T a_w^2(t)dt]^{\frac{1}{2}}$ [39].
2) The vibration dose value (VDV) is the cumulative value of vibration dose. VDV is calculated by the fourth power of the acceleration time in a unit of meters per second to the power of 1.75 (m/s$^{1.75}$) and expressed by: $VDV = \{\int_0^T [a_w(t)]^4 dt\}^{\frac{1}{4}}$. VDV represents a cumulative dose increasing with the length of time measured [39].
3) The daily exposure [A(8)], which is averaging RMS over an 8-hour exposure day.

Whole body vibration includes both constant vibration and mechanical shock. The continuous vibration originates from a vehicle's engine power as well as operating features; the mechanical shock is generated when driving over uneven surface or obstacles [40].

When assessing WBV impact on the human body, these standardized metrics are used. RMS and A(8) are first calculated for WBV analysis, followed by the crest factor (CF). CF is the ratio of the maximum instantaneous peak value to its RMS value [38]. When crest factors are larger than 9, substantial peaks exist, and the basic value (RMS) does not adequately describe the whole body vibration exposure. Since it is calculated by the fourth power, VDV is more sensitive to shocks compared to RMS. CFs above 9 indicate the existence of mechanical shocks, where further VDV analyses are needed to achieve a comprehensive WBV profile. For CFs less than 9, RMS and A(8) are sufficient to evaluate vibration.

1.6 WBV and LBDs

Research conducted in populations with occupational vehicle use reveals high LBP prevalence rates with WBV exposures. Locomotive engineers in New Zealand, with a relative high exposure to WBV, experienced more frequent LBP (1-year prevalence of 90% and lifetime prevalence of 87%) than other occupations [Odds Ratio (OR) = 1.77, 95%CI, 1.19 to 2.64] [41]. Armoured vehicle drivers with LBP experienced a significantly higher WBV exposure than drivers without LBP, and the X-axis vibration (4.69 eVDV $ms^{-1.75}$) contributed significantly to LBP (OR=1.94, 95%CI, 1.02 to 3.69) [42]. WBV exposure among industrial workers was also found to be associated with LBP (OR=1.7, 95%CI, 1.0 to 3.0) [43].

There is consistency among epidemiological studies that WBV is associated with LBD. Literature reviews conducted before 2000 present a strong relationship between WBV and LBD [3]. This strong association has also been found by a recent meta-analysis with an OR of 2.17 and a 95% CI ranging from 1.61 to 2.91 [44]. Within the agricultural context, farming tasks generally require a lot of driving where farmers are exposed to WBV when operating various farm equipment. Driving heavy equipment vehicles, such as tractors, harvesters, and loaders, are strongly associated with LBDs (meta-Relative Risk = 2.21) [45]. New Zealand farmers are under high mechanical shocks with quad bike driving; the higher the shock, the higher OR value observed between mechanical shock and 1-year prevalence of LBP [46]. Among all age groups with WBV exposures, Polish farmers had more complaints of LBP and faced a higher risk of chronic back pain than other occupations; and increasing the WBV exposure was significantly related to LBP episodes [47]. The above results demonstrate the trend between increasing vibration or mechanical shock exposures and an increased risk of LBP. More research on exposure assessment of mechanical shock combined with vibrations and on evaluating the health impact of such exposures in farming is needed.

In the year 2011, the Census of Agriculture described a total of 36,952 farms in Saskatchewan with an average land area of 1,668 acres, which comprised 18% of Canadian farms [48]. During the period of 2006 to 2011, there has been a 15% increase in the average Saskatchewan farm size, but a 16% decrease in the total number of farm operators to 49,475. Larger farms are being operated by fewer farmers, with more machinery use and longer machinery operating hours. More WBV research on these unique Saskatchewan circumstances is needed in order to plan effective strategies for LBD prevention.

1.6.1 Mechanisms from WBV exposure to LBDs

WBV produced by mobile machines usually has a low-frequency spectrum (less than 10 Hz), while the human body resonance frequency of a seated person is typically 5Hz [49]. It is possible that this vibration resonance effect has an adverse impact on the lower back area [49].

LBDs are caused by multifaceted factors, and WBV is but one of many physical risk factors that can interact with other factors in developing back problems. It is suggested that the interaction between WBV, posture, and manual material handling plays an important role in LBDs [50]. For example, drivers sitting with awkward postures, such as forward bending, while exposed to WBV are considered at higher LBD risks [42]. It is also argued that long-term WBV exposure can lead to nutritional and structural impairment of the lumbar discs reducing disc height and affecting spinal function; which may relate to corresponding spine symptoms and related disability [51].

1.7 WBV exposure limit

In order to promote health and control WBV exposure, exposure standards have been proposed. The Japanese Society for Occupational Health has recommended a WBV exposure limit of 0.35 m/s^2 [A(8)] since there is not enough evidence on the dose-response relationship between low acceleration WBV (under 0.35 m/s^2) and LBP in Japanese working populations [52]. ISO 2631-1 [38] indicates a vibration frequency range which can have an effect on health. The frequency range for motion sickness is from 0.1 Hz to 0.5 Hz, and for health, comfort, and perception it is from 0.5 Hz to 80Hz. In order to protect workers from the adverse health outcomes of vibration, the European Vibration Directive also sets exposure limits for vibration [53]: daily action values of 0.5 m/s^2 for constant vibrations or 9.1 $m/s^{1.75}$ for vibration dose values, and daily limit values of 1.15 m/s^2 for constant vibrations or 21.0 $m/s^{1.75}$ for vibration dose values.

1.8 Exposure Assessment methods

In ergonomic epidemiology, external exposures can be evaluated by three methods [54]: (1) subjective judgements obtained from workers or experts; (2) observations at the workplace; (3) direct measurements on site or during lab simulations.

The direct measurement method is the gold standard for WBV [38]. By setting up the seat pad on the surface of the seat, the accelerometer is able to capture vibration transmitted from the vehicle to the human body via the pelvis. However, this method is costly in terms of purchasing special vibration equipment, training researchers to collect data, and spending time collecting and processing measurements. Indirect WBV exposure information can also be obtained via survey, work histories or interview, where workers report their perceptions of their exposure. It is less expensive and easier to gather than direct measurements, but these low-fidelity measurements may result in a biased assessment of individual vibration exposure level [55].

An alternative method is to build a statistical prediction model by matching possible predictors to explain sub-samples of direct vibration measurements. This has been successfully performed for several occupational exposures, such as dust [56], particulate matter [57], as well as WBV [58, 59]. For example, Chen *et al.* conducted a study among 237 Taipei taxi drivers to identify predictors of WBV using a mixed effect prediction model, where results found driving speed as the main predictor and others include: vehicle manufacturer, engine size, seat cushion, traffic period, driver body weight, and age [58]. Village *et al.* performed vibration assessment among heavy industrial workers to investigate WBV predictors through mixed effect regression models; they also found driving speed to be an important predictor, as well as industry and vehicle type [59]. The vibration prediction models have been shown to be valid in estimating WBV from the above research. Typical results include an 11% prediction error [58] and about 60% of the variance explained [59]. However, neither of these models focus on agriculture or farm machinery. It would be helpful to predict the patterns of agricultural vibration exposure by using more cost-efficient predictors rather than direct measurements. This will help identify avenues for prevention of WBV exposure, and also be useful for future epidemiological studies since it allows for inexpensive assessment of a large sample. Therefore, valid exposure prediction models are needed to explore WBV predictors in the agricultural context.

1.9 WBV predictors

The mechanical vibration transmitted from seat to the body comes from machines or vehicles used in the workplace. In agriculture, common farm machines and related farm tasks are as follows: cultivator for loosening the soil and killing weeds; seeder for planting seeds; sprayer for liquid solutions (herbicide or pesticide); swather for cutting and forming hays or crops; combine for harvesting crops; truck for hauling grains; baler for making bales; most essentially a tractor, which can be applied to multiple tasks.

Vehicles differ in size, structure, and functions. Vehicle type is a potential predictor for WBV [60]. The exposure to WBV from tractors, harvesters, loaders, and ATVs have been studied separately as a risk factor for LBDs [45, 46]; while other forms of farm equipment, such as sprayers, seeders, swathers, *etc.* require further research. Comprehensive WBV research on various farm machinery will help in the further understanding of exposures in the agricultural environment.

When considering the transmission of vibration, vehicle features, such as seat cushion, seat suspension, tire type, and backrest, are also potential WBV predictors [60]. For example, compared to rigid seats, cushioned seats may help to attenuate load and therefore potentially prevent structural changes of lumbar discs associated with WBV [51]. Seats with mechanical or air suspension can both decrease the WBV level experienced by the driver with air suspension demonstrating a better effect than mechanical suspension [61].

The type of terrain that the vehicle has driven on is also quite important, as it affects the level of vibration and shock. For example, quad bike workers driving in New Zealand rural terrain were found to be exposed to higher amounts of mechanical shock [62].

To summarize, more research about other possible predictors including vehicle type, and vehicle characteristics, such as tire size, load type, vehicle weight, horsepower, transmission, gears, *etc.* is needed to best describe vehicle features in vibration measurements. The American Conference of Governmental Industrial Hygienists (ACGIH) suggested controlling WBV exposure from multiple sources by proper design of the seat area, a good vehicle suspension system, avoidance of awkward postures while driving, and taking frequent stretch breaks [63]. Knowing more about WBV predictors will likely provide further ideas on what to do for providing effective WBV controls.

2.0 Objectives

To date, there have been no exposure assessment studies involving direct measurement of WBV in Saskatchewan agricultural workers. Little is known about specific patterns of WBV exposure, which limits efforts to prevent both WBV exposure and ultimately, LBDs. In order to understand the level and duration of WBV exposure and develop recommendations, more information is needed on what factors decrease or increase WBV exposure. By identifying effective predictors of WBV from this pilot study among farmers, it will support the evaluation of WBV at a population level, and likely save money and time spent on direct vibration measurement.

This thesis contains two manuscripts, each addressing a different objective:

1. The objective of Manuscript 1 is to describe WBV exposure patterns in Saskatchewan farmers
2. The objective of Manuscript 2 is to present the development of a model to predict WBV and suggest strategies to limit exposure in Saskatchewan farmers

Chapter 2: Manuscript1

Whole Body Vibration Exposure Patterns in Canadian Prairie Farmers

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Submitted to: Ergonomics

2.1 Abstract

Whole body vibration exposure is a significant physical risk factor associated with low back pain. This study assessed farmers’ exposure to whole body vibration, as per the ISO 2631-1 standard, on the Canadian Prairies of Saskatchewan. Eighty-seven measurements were collected from 8 different agricultural machinery types including: tractor; combine; pickup truck; grain truck; sprayer; swather; all-terrain vehicle; and skid steer. The mean vector sum values of vibration metrics were, 0.78 m/s^2 (frequency weighted root mean squared acceleration), 27.64 (crest factor), 10.02 $m/s^{1.75}$ (vibration dose value). Whole body vibration varies substantially within farm machines. The high exposures, along with the advanced age of this workforce, presents a substantial risk to their health requiring action to reduce vibration in the farming environment.

Keywords: agriculture, farm machinery, hazard, mechanical shock, occupational exposure

Practitioner Summary: Those working in the agricultural sector can be exposed to whole body vibration exposures. Assessing ergonomic risk factors for whole body vibration is critical in promoting a safe occupational environment in farming. Farmers use various types of farm equipment that may expose them to high levels of vibration, likely presenting a substantial risk to farmers’ musculoskeletal health.

2.2 Introduction

Whole body vibration refers to the mechanical vibration or shock transmitted from mobile equipment to the human body [39]. Human responses to whole body vibration span physiological systems (cardiovascular, respiratory, endocrine, metabolic, motor, sensory, central nervous, and skeletal), which can lead to pathological changes in organs [49]. Specifically, whole body vibration at low frequencies (below 10 Hz) is associated with increasing risk of back problems [38]. Thirty-seven percent of low back pain in the workplace is attributed to ergonomic risk factors including whole body vibration, awkward postures, heavy lifting, and repetitive workloads [64]. Farmers are a working population that typically experience high adverse ergonomic exposures [65], as well as the high 1-year prevalence of musculoskeletal disorders (60%-93%) [15]. Most epidemiological studies have focused on back pain as the most commonly reported health effect from exposure to whole body vibration [66], and on whole body vibration as a significant contributor to back pain [3, 44].

The global trend of agricultural mechanization means whole body vibration is a common exposure in farmers' work environments. Worldwide, the rapid development of agricultural mechanization promotes productivity, so machinery use has become a predominant feature of farming. Developing countries are introducing policies to encourage manufacturing and purchase of high-efficiency farm equipment to enhance economic growth; where the total number of tractors is estimated to increase 6 to 10% annually [67]. Meanwhile, developed countries are adopting and replacing their equipment with newer and more advanced technologies [68].

In farming, whole body vibration exposures have been directly measured during on-farm use of quad bikes in New Zealand [69], tractor use in Finland [70], and common machinery use in

Japan [71, 72] and Poland [73, 74]. The farming context influences the machinery use pattern. Little research has been conducted on directly-measured whole body vibration exposure on the Canadian Prairies. Over 80% of Canada's cropland is located on the Canadian Prairies, which is comprised of the provinces of Alberta, Saskatchewan, and Manitoba [75]. In this area grain production has accounted for the major part of prairie agriculture, with recent diversification into specialty crops such as peas and lentils [76]. Previous research has highlighted the significance of measuring physical hazards on farms as an effort to identify factors for injury prevention [77]. The objectives of this study are to observe the types of farm machinery used in Saskatchewan, measure farmer's exposure to whole body vibration, quantify its severity and variability, and help guide future interventions for occupational health and safety.

2.3 Materials and Methods

A 1-year field study was conducted in the province of Saskatchewan, Canada. The owners or managers of 60 farms that met the criteria being located within 400 km of Saskatoon, Saskatchewan and previously participated in the Saskatchewan Farm Injury Cohort Study [78] were contacted via mailed letters. Adult farm workers who conduct farm tasks more than 12 weeks per year were eligible to participate. Signed consent forms were obtained. Farm tasks vary between seasons, and the use of farm machinery was highly seasonal. In order to capture this variability, three visits were made during spring (March to May), summer (June to August), and autumn (September to November) throughout the 2015 calendar year.

During measurement visits, farmers performed their regular tasks using their regular equipment. Farmers were considered to be exposed to whole body vibration once they were on the mobile equipment; and if any driving task occupied more than 5 minutes, a whole body vibration measurement was made. In order to minimize interruption, initial setup was undertaken before the start of work and recording was completed at the end of the task.

Among the possible vibration transmission interfaces (e.g. seat, cab floor, backrest, armrest, and steering wheel), the seat surface is most commonly used for vibration assessment when working in a seated position. The International Organization for Standards (ISO) 2631-1 advocates the use of a rubberized seat pan with an embedded tri-axial accelerometer, and the use of frequency corrected accelerations to standardize the exposure [38].

All measurements were made on the seat surface as defined in ISO 2631:1997 [38]. A Series 2A tri-axial accelerometer (NexGen Ergonomics, Montreal, CA) that captures vibration signals in fore and aft (X), lateral (Y), and vertical (Z) axes was mounted into a rubberized seat pad, and fixed to the seat (Figure3). Vibration data were recorded using an MWX8 DataLog (Biometrics Ltd., Newport, UK) with a sampling rate of 1000Hz and an 8th order elliptical anti-aliasing filter set at 100Hz. The data recorder was stored safely in a protective case behind the seat area if there was space for it (Figure 3b), otherwise, it was placed in a waterproof pouch (Figure3 a, c, d) at a secure spot close to the identified seat area.

Raw vibration data were first edited in DataLog PC software 9.01 (Biometrics Ltd.) to remove portions of recorded data that were not real mechanical vibration. For example, machines might be turned on to warm up but not moving (‘idle’ time) or even be turned off (‘quiet’ time). These are not infrequent scenarios in farming, where non-continuous driving may occur, during the first stage of harvest time where farmers conduct quality tests on sample products from each field. This involves a cycle of driving a combine, stopping and getting off, sending products for test, and then driving again. When the harvest is officially started, farmers usually start driving a combine until the tank is fully filled, stopping and transferring products into a grain truck, and driving again. When a farm machine was stopped, engine idling process produces a high-frequency, low-amplitude vibration that has a low health risk to the human body, and engine ‘quiet time’ produces no vibration at all, and therefore both types of data were deleted from the original file. Decisions of non-mechanical vibration were made by inspecting the Vibration Frequency Spectrum Graph produced by Biometrics software. Vibration with a frequency range beyond a 0.5Hz-80 Hz range was considered either idling or engine quiet time.

The Vibration Analysis Toolset software (VATs 3.4.4, NexGen Ergonomics, CA) was used for vibration data analysis. We applied standardized whole body vibration metrics of frequency weighted root-mean-squared (RMS) acceleration, peak, crest factor, and vibration dose value (VDV), described in ISO2631-1(1997) [38].

The frequency-weighted RMS acceleration in each axis is mathematically expressed as:

$$a_w = [\frac{1}{T}\int_0^T a_w^2(t)dt]^{\frac{1}{2}}. \qquad \text{[Equation 1]}$$

In this study, the vector sum of RMS from three orthogonal axes is calculated by applying the correction factor 1.4 to X- and Y- axes, while factor 1.0 to Z-axis, as follow:

$$RMS_{sum} = \sqrt{(1.4a_{xw})^2 + (1.4a_{yw})^2 + a_{zw}{}^2}\ . \qquad \text{[Equation 2]}$$

The peak value is the instant maximum acceleration during the measurement duration. Crest factor is the ratio of peak divided by RMS value, considered as a way to characterize the mechanical shock profile of a measurement. When the crest factor is larger than 9, ISO2631-1

[38] recommends that RMS is not enough to describe the vibration and VDV would be a more appropriate metric.

VDV is the accumulative vibration value that emphasizes shocks with an equation of:

$$VDV = \{\int_0^T [a_w(t)]^4 dt\}^{\frac{1}{4}} . \qquad \text{[Equation 3]}$$

Likewise, the vector sum was also calculated as:

$$VDV_{sum} = \sqrt{(1.4VDV_{xw})^2 + (1.4VDV_{yw})^2 + VDV_{zw}{}^2} . \qquad \text{[Equation 4]}$$

SPSS (IBM Inc., Armonk, NY, USA) was used for descriptive analysis (mean, standard deviation, and range) on vibration metrics across machine types. The total daily whole body vibration exposure regarding RMS is termed A(8) for an 8-hour work day. In this study, each measurement day was limited to 4-6 hours since a large portion of each day was spent traveling back and forth to rural farms. In order to get an estimate of daily exposure levels, the partial A(8) for each machinery was calculated based on the vertical RMS acceleration results in this study, using Equation 5, where *T measured* represents the measurement period, and T_0 refers to an expected daily duration of 8 hours.

$$Partial - A_z(8) = RMS_z \sqrt{\frac{T_{measured}}{T_{0(8hour)}}} \qquad \text{[Equation 5] [66]}$$

2.4 Results

2.4.1 Farm and Farmer Characteristics

Twenty-one family-owned farms participated in the study, including 15 grain farms, 2 animal farms, and 4 mixed-production farms. A total of 40 male farmers were measured during their driving tasks. Basic demographic information was obtained from the 26 participants who were mostly farm operators, they had a median age of 55 years old, and mean body mass index of 28.8 kg/m^2 (Table1.).

2.4.2 Whole body vibration results

Table 2 shows the whole body vibration results (RMS, peak, crest factor, and VDV) categorized by types of farm machinery. Figure 4 shows boxplots of RMS and VDV classified by machine type. A total of 87 measurements were gathered on 8 different types of equipment. The number of measurement on each farm machine demonstrates the corresponding frequency of use during farm visits. The tractor was the most frequently used machine with 26 measurements while skid steer was the least used with only 2 measures. Pictures are attached in Appendix D to demonstrate the range of agricultural machinery measured in the present study.

The measurement duration varied by machinery, reflecting the duration pattern of farm tasks. The shortest ride was 6 minutes on a pick-up truck. The longest ride was 4 hours and 45 minutes on a tractor. On average, combine, swather, and tractor were more likely to have long-ride tasks around 2 hours; ATV and skid-steer were more likely to have short rides of 0.5 hours; pick-up trucks, grain trucks, and sprayers were commonly involved in one-hour rides. Tasks like harvesting, swathing, spraying and seeding can normally occupy more than 8 hours of a farmer's workday, depending on the season. Transportation within the farm area usually takes 1-4 hours of the day, and travelling beyond the farm was longer, around 6-9 hours. Ranching animals on an ATV or pickup truck are scattered throughout the day, for example, 30 minutes in the morning and 30 minutes in the afternoon. Maintenance work using a skid-steer could take all day but the actual exposure time on the vehicle is short (approximately 30 minutes) due to frequently stepping onto and off the vehicle.

2.4.3 Frequency weighted RMS accelerations

For all vehicle types, the vertical direction (Z) had the highest RMS accelerations which contributed most to the vector sum. The mean RMS vector sum was 0.78 m/s^2 with the maximum measurement 1.21 m/s^2 from ATV and the minimum of 0.47 m/s^2 on the combine. Higher vibration levels were also observed on swathers (0.96 m/s^2), grain truck (0.95 m/s^2), and tractor (0.89 m/s^2). Relatively high values were noted to come from sprayers (0.69 m/s^2), pick-up truck (0.69 m/s^2), and skid-steers (0.6 m/s^2).

2.4.4 Peak and Crest factor

Peak denotes the highest RMS acceleration reached during the measurement duration. As with the RMS metric, the greatest peak value was from the vertical axis. On the whole, the mean peak vector sum (16.89 m/s^2) was 24.8 times larger than the mean RMS acceleration vector sum (0.78 m/s^2), indicating a likely high contribution of mechanical shocks. Not surprisingly, the vertical (Z) crest factor was the greatest with an average of 40.01. 97.7% of crest factor sums was above 9.

2.4.5 Vibration dose value

Vibration dose value integrates over time of the frequency weighted accelerations to the fourth power, which is more sensitive to mechanical shocks. As with RMS accelerations, the vertical axis was the dominant axis with the highest value among three directions. Higher VDV vector sums were from skid steers (13.59 $m/s^{1.75}$), ATVs (11.67 $m/s^{1.75}$), tractor (11.10 $m/s^{1.75}$), swather (10.10 $m/s^{1.75}$), combine (9.77 $m/s^{1.75}$), and grain truck (9.74 $m/s^{1.75}$); lower VDV sums were from pick-up truck (8.52 $m/s^{1.75}$) and sprayer (7.84 $m/s^{1.75}$).

2.4.6 Partial-A(8)

Partial-A(8) is part of the daily exposure value of RMS accelerations from a single machinery type. The average partial A(8) is 0.18 m/s^2.

2.5 Discussion

According to the 2010 Census of Agriculture [48], there were 36,952 total farms reported in Saskatchewan with an average farm size of 1668 acres; 60% of the farming area was cropland, and farm operators had an average age of 54.2 years. The farmers in this study had a median age of 55, suggesting a representative sample of Saskatchewan farm operators. Grain crops were the dominant farm product in the present study, consistent with Saskatchewan being the largest grain production province in Canada [48].

In this study, the range of RMS vector sum was from 0.31 m/s^2 to 2.33 m/s^2, which is similar to Futatsuka *et al.* 's findings on agricultural machinery use ranging from 0.35 m/s^2 to 1.63 m/s^2 [79]. The maximum value (2.33 m/s^2) is much higher than theirs (1.66 m/s^2), which may be due to the high vibration magnitudes from the ATV measurements. Futatsuka *et al.* conducted test rides among common machine use in Japanese farming; they observed similar vibration magnitudes from three axes and results were only focused on RMS accelerations with no report of VDV and crest factor [79].

Within all tractor measurements in this study, farm tasks like lawn mowing and cultivating were observed to have the highest vibration magnitudes while the lowest levels were from transportation tasks. These findings are consistent with previous research. Solecki [73] found higher RMS vector sum (range 0.87 -1.78 m/s^2) in farming activities of spraying fertilizers, aggregating soil, mowing grass, and swathing hays; lower sum values (range from 0.25 -0.58 m/s^2) from activities of seeding grains, harvesting maize, digging potatoes/sugar beet, and transporting on field roads. In this study, the highest vibration values were from the vertical direction (Z) and high crest factor values (above 9), which are also consistent with Solecki's finding [73].

In the present study, the variation of whole body vibrations may be due to the different features in farm tasks, vehicle (e.g. year, make and model, seat suspension, tire, brand, and load type), terrain condition, and farmers (e.g. age, size, driving skills). To illustrate the effect these conditions would likely to have on exposure, we compared the best and worst-case tractor scenario regarding vector sums of RMS accelerations and VDVs, separately, as follows.

The highest RMS sum was from a lawn mowing task on a 2013 Leading Solution R4041. This tractor was equipped with air suspension seat, wheel tires, forklift load in the front, and mower pulled behind. The whole ride lasted for 2.53 hours on cropland. The operator was 47 years old and who had been grain farming more than 10 years. Large constant vibrations and shocks were demonstrated by the high vector sum values of RMS (1.64 m/s^2), crest factor (12.28), as well as VDV (19.93 m/s$^{1.75}$). The highest VDV vector sum was from a summer-fallow task on a 1978 Versatile 800 Series2. This tractor had spring suspension seat, wheel tire, and a cultivator load pulled behind. The total task duration was 4.75 hours on a grain farm. The 64-year-old operator experienced persistent high vibrations and shocks during the measurement, demonstrated by high vector sums of crest factor (16.37), VDV (25.18 $m/s^{1.75}$), as well as RMS (1.55 m/s^2).

The lowest RMS vector sum was from a grain transportation task using a 2013 John Deere 9510RT, which equipped with air suspension seat, track tires, and a full load of grain. This occurred on a grain farm, where a farm employee in his 20s drove for 1 hour on both cracked earth terrain and on-farm field roads. Low vibration vector sums were observed from RMS (0.40 m/s^2) and VDV (6.26 $m/s^{1.75}$), but high crest factor (33.15) suggesting large temporary bumps. The lowest VDV vector sum was from another transportation task of a grain bin on farm property at low speeds with a 1984 Case 4894 Tractor, with air suspension seat, dual wheel tires, and the hoist lifting a grain bin behind. The task was about 30 minutes on a grain farm conducted by an experienced farm operator. Low vector sums of VDV (4.94 $m/s^{1.75}$) and RMS (0.5 m/s^2) but also combined with high crest factor (20.49), which reveal transient but high shocks that might be caused by the heavy load pulled behind the tractor over unpaved terrain.

In this study, the mean Z-axis daily VDV on ATVs (9.88 $m/s^{1.75}$) was lower than what Milosavljevic *et al.* found on agricultural quad bike use (17.2 $m/s^{1.75}$) in New Zealand[80]. VDV is a cumulative vibration dose that will increase with measurement time[38]. For some of the machinery use, we were either not able to measure the full day exposure or to collect self-reported driving durations. However, researchers observed that a normal harvesting day using combine would last for 8 hours or longer in the present study. The daily VDV in the vertical direction would reach 13.24 $m/s^{1.75}$ on a combine using Equation 6, where $T_{measured}$ refers to the mean measured duration of 1.91 hours, $VDV_{z\,(measured)}$ denotes to the measured VDV of 9.26 $m/s^{1.75}$ (Z-), and t_n represents the expected 8-hour daily exposure.

$$VDV_z = VDV_{measured} \sqrt[4]{\frac{T_{0(8hours)}}{T_{measured}}}$$ [Equation 6] [66]

2.5.1 Health effects of vibration

For evaluation of the health effects of whole body vibration, ISO 2631-1[38] has published a health guidance caution zone, based on daily Z-axis exposure results. The lower and upper bounds for weighted RMS acceleration and VDV are, 0.45 m/s^2 and 0.9 m/s^2, 8.5 $m/s^{1.75}$ and 17 $m/s^{1.75}$, respectively. When the expected daily exposure in the vertical direction is above the lower limit, a health risk is likely to exist, and when below the lower limit, the probability of health risk is low or unclear.

For the purpose of a health risk evaluation using the health guidance caution zone (HGCZ), we made an assumption that each individual series of whole body vibration measurements was the only driving each farmer conducted on the measurement day. Figure 4 shows boxplots of daily vibration exposure categorized by machinery type, with the estimated daily exposure of frequency-weighted vertical RMS acceleration (Top) and daily VDV exposure (Bottom). These results are superimposed over the health guidance caution zones presented in shades of grey. The estimated daily exposure of vertical RMS acceleration was the partial A(8). Since VDV calculation (Equation3) has integrated time, the daily VDV *z-axis* exposure would be what this study has measured from the vertical axis.

Ninety-eight percent of the daily frequency-weighted *z-axis* RMS measurements was located under the HGCZ (less than 0.45 m/s^2) with low or unclear risk. Forty-one percent of the daily *z-axis* VDV measurements were located within or above the ISO HGCZ, indicating that health risks are likely to exist. Since VDV should be emphasized in high shock contexts, the use of frequency-weighted RMS for agricultural whole body vibration exposure is likely to underestimate vibration-associated health risks.

VDV measurements that exceeded the lower bound of HGCZ were present among all types of machinery in the current study; the proportion of measurements above the 8.5 $m/s^{1.75}$ limit varied by machinery type: all-terrain vehicle (100%), swather (60%), high-clearance sprayer (50%), skid steer (50%), tractor (38.5%), grain truck (38.5%), pickup truck (35.7%), combine (29.4%). In particular, the all-terrain vehicles often used in ranching generated high *z-axis* VDV (9.88 $m/s^{1.75}$) on average with a mean driving duration of only 0.57 hours. This is compared to a previous study on agricultural quad bike use where the daily exposure was 17.2 $m/s^{1.75}$ after an average of 2.1 hours driving in New Zealand [80]. The relatively lower daily VDV exposure on all-terrain vehicle use in the current study is likely related to the shorter vehicle driving time and less hilly farm terrain conditions.

The use of multiple machines per day in farming is common. The European Vibration Directive 2002/44/EC [39] has further set daily exposure thresholds for workplace RMS and VDV exposures. The lower limit is the daily action value, 0.5 m/s^2 for RMS acceleration and 9.1 $m/s^{1.75}$ for VDV; when these levels are reached action should be taken by the employer to reduce exposure. The daily limit values of 1.15 m/s^2 for RMS acceleration and 21 $m/s^{1.75}$ for VDV represent exposures that workers should not be exposed to under any circumstance.

For the purpose of evaluating the farming work daily exposure, we adopted the calculation method from the European Vibration Directive 2002/44/EC [39] with two differing typical work day examples extracted from this study, one on a grain farm and one on an animal farm. As shown in Table 3, 'Example A' was from a livestock ranch, the farmer first drove a pickup truck on pasture to feed cattle, then he transferred onto a quad bike. The daily A(8) exposure was 0.19 m/s^2, which was below the daily action limit; the daily VDV exposure was 11.58 $m/s^{1.75}$, which was above the VDV daily action limit. 'Example B' was from a grain farm; he transferred between three vehicles with four rides include quad bike (ride1), tractor (ride2), pickup truck (ride3), and same pickup truck (ride 4). The daily A(8) and VDV exposures were 1.13 m/s^2 and 12.34 $m/s^{1.75}$, both above the daily action limit.

From the above examples, the animal farming day was below the action limit while the grain farming day was above the limit; however, on both days, VDV daily exposures exceeded the daily action bound. With crest factors above 9, the use of A(8) daily exposure likely underestimates the vibration severity, and it is recommended that the VDV is the more appropriate metric to use. It is also important to consider that the farming population is subject to long-term exposures with long working days over many years since many farmers start working on farms and operating machinery from a young age. With more and longer driving tasks, the working exposure would be considered unsafe for farmers and calls for preventative strategies.

Both long-term and high-intensity whole body vibration exposures increase the risk of experiencing LBDs [38]. Therefore, either a reduction of the exposure duration or exposure magnitude would help protect farmers from vibration hazards [66]. One strategy would be to break-up long driving tasks into shorts chunks with breaks for stretching or other tasks. This strategy will not cut down the total driving hours, but it has potential to decrease the cumulative exposure effect on the body. Another strategy is to add more vibration and mechanical shock absorbing buffer to decrease the dose that vibration transmitted to the human body through additional cushions or seating suspension.

2.5.2 Strengths and limitations

This field study collected measurements for a full year across 3 farming seasons to capture multiple types of farm machines. The direct measurement of whole body vibration is considered a gold standard for vibration exposure assessment and provides accurate vibration levels. The findings capture substantial variability by representing multiple farm tasks, farm machines, farm products, and individual farmers.

One limitation of this study was an inability to measure farmers' full working day and to collect information on farmers' self-reported duration of unmeasured tasks either. For this reason, the calculations of A(8) may be underestimated. However, farm work does not have a typical 8-hour day. Even after planning a measurement visit with farmers, researchers were unable to predict which tasks would be done and what machinery would be used on a given measurement day. Typical of field-based ergonomic assessments, substantial time and research expense was spent making direct onsite measurements [81], and we were only able to follow the farmer and measure whatever occurred during the measurement day. Lower cost, higher efficiency whole body vibration assessment methods are needed in the future to enable research with larger samples.

A further limitation of this study was an inability to assess the health risk for each farmer based on ISO 2631-5 standards [82], which requires information on hours of exposure for the number of working days and farming years, an important standard for farming exposure in this study. We concluded that shocks existed, and VDV should be the representative metric due to crest factors above 9; this is especially important to consider since health disorders are more influenced by peak values and could be underestimated by calculating frequency-weighted accelerations alone [38]. Prior research has found significant associations between whole body vibration and musculoskeletal disorders; full-day vibration and shock exposures of quad bike use on 130 farmers using ISO 2631-5 standards indicated a significant relationship between whole body vibration and LBP 1-year prevalence, and strong association of whole body vibration on the 1-year prevalence of neck pain [62].

2.6 Conclusions

Farmers in the Canadian prairie province of Saskatchewan are exposed to considerably high whole body vibrations and shock exposures. Future intervention research is needed to protect farmers in the work environment. Future whole body vibration assessment should focus on both ISO 2631-1 and ISO 2631-5 standards, as well as determine how to best model exposure based on machinery, task, and terrain characteristics as an alternative way of exposure assessment.

Table 1. Participant and farm characteristics.

Farmer workers (N= 26)	
Sex (Male %)	100
Age, years old (Median, Interquartile range)	55, 40-62
Body mass index (Mean ± Standard deviation, Range)	28.8 ± 4.71, 19.93-41.23
Farm (N=21)	
Commodity	
Grain % (N=15)	71.4
Mixed % (N=4)	19
Animal % (N=2)	9.6
Acreage, acres (Median, Interquartile range)	4000, 1850-7120

Table 2. Whole body vibration magnitude on different farm equipment.

Machinery type	**Duration (min)**		**RMS (m/s^2)**				**Peak (m/s^2)**				**Crest Factor**				**VDV (m/s$^{1.75}$)**				**Partial-A(8)**
	Mean	Range	Mean				Mean				Mean				Mean				Mean
(Measurement	(SD)		(SD)				(SD)				(SD)				(SD)				(SD)
Numbers)			X	Y	Z	Sum	X	Y	Z	Sum	X	Y	Z	**Sum**	X	Y	Z	**Sum**	Z-axis
Tractor	103.11	16-285	0.37	0.39	0.44	0.89	5.08	4.77	15.26	18.49	14.85	12.71	38.40	**22.10**	5.46	5.68	8.70	**11.10**	0.20
(26)	(70.52)		(0.13)	(0.15)	(0.22)	(0.33)	(2.22)	(2.06)	(6.88)	(7.11)	(8.19)	(5.14)	(18.67)	**(8.09)**	(2.09)	(2.56)	(4.94)	**(5.17)**	(0.16)
Combine	114.68	9-217	0.19	0.16	0.31	0.47	3.49	3.14	18.25	19.72	19.58	17.68	55.85	**40.09**	3.50	3.10	9.26	**9.77**	0.15
(17)	(69.52)		(0.05)	(0.04)	(0.10)	(0.11)	(3.29)	(3.75)	(10.96)	(12.48)	(17.21)	(15.18)	(19.70)	**(16.87)**	(2.21)	(3.19)	(8.03)	**(8.15)**	(0.09)
Pick-up Truck	50.41	6-200	0.20	0.28	0.49	0.69	3.64	3.80	18.42	20.15	17.95	13.24	36.71	**28.34**	2.87	3.57	7.87	**8.52**	0.14
(14)	(56.26)		(0.07)	(0.09)	(0.11)	(0.17)	(2.98)	(2.44)	(12.15)	(12.78)	(10.90)	(5.34)	(19.26)	**(14.20)**	(1.95)	(1.85)	(4.41)	**(4.67)**	(0.08)
Grain Truck	58.13	9-236	0.41	0.32	0.54	0.95	4.82	4.24	14.27	17.90	14.21	14.03	28.90	**22.68**	4.53	3.77	7.65	**9.74**	0.17
(13)	(61.17)		(0.40)	(0.10)	(0.15)	(0.51)	(3.11)	(1.13)	(7.26)	(5.93)	(6.78)	(4.19)	(18.79)	**(12.80)**	(2.69)	(0.62)	(2.36)	**(2.70)**	(0.09)
Sprayer	63.54	17-116	0.22	0.29	0.45	0.69	2.80	3.20	15.85	17.50	12.48	11.39	36.68	**26.40**	2.83	3.57	7.00	**7.84**	0.16
(6)	(36.07)		(0.02)	(0.07)	(0.13)	(0.12)	(0.75)	(0.91)	(10.77)	(9.76)	(3.31)	(3.99)	(27.73)	**(16.98)**	(0.53)	(0.81)	(2.80)	**(2.36)**	(0.06)
Swather	135.42	49-240	0.42	0.33	0.59	0.96	3.34	3.18	16.22	17.74	8.55	9.99	29.36	**20.10**	5.54	4.23	8.45	**10.10**	0.29
(5)	(77.68)		(0.17)	(0.10)	(0.18)	(0.32)	(0.72)	(0.75)	(9.23)	(8.67)	(2.67)	(2.26)	(18.42)	**(12.33)**	(1.52)	(0.72)	(2.25)	**(2.42)**	(0.08)
All-terrain Vehicle	34.14	14-76	0.44	0.48	0.77	1.21	5.80	5.16	17.70	21.10	13.32	10.39	23.05	**17.43**	5.65	5.44	9.88	**11.67**	0.19
(4)	(28.73)		(0.19)	(0.08)	(0.06)	(0.21)	(2.41)	(2.72)	(2.09)	(3.48)	(4.65)	(4.60)	(2.49)	**(0.67)**	(2.49)	(1.67)	(1.15)	**(2.41)**	(0.07)
Skid steer	38.97	31-47	0.22	0.20	0.43	0.60	2.90	2.60	35.97	36.75	13.00	13.52	92.05	**64.27**	3.26	2.90	13.44	**13.59**	0.12
(2)	(11.07)		(0.02)	(0.02)	(0.06)	(0.04)	(0.70)	(0.52)	(39.62)	(38.96)	(2.07)	(4.13)	(106.17)	**(70.13)**	(0.10)	(0.44)	(9.45)	**(9.30)**	(<0.001)
Total	84.65	6-285	0.31	0.31	0.46	0.78	4.22	3.99	16.89	19.34	15.54	13.63	40.01	**27.64**	4.30	4.25	8.55	**10.02**	0.18
(87)	(68.25)		(0.20)	(0.14)	(0.19)	(0.35)	(2.68)	(2.41)	(10.30)	(10.42)	(10.45)	(8.04)	(25.01)	**(17.02)**	(2.31)	(2.38)	(5.07)	**(5.27)**	(0.12)

Note: aRMS ─ Frequency weighted root-mean-squared acceleration; Peak ─Maximum instantaneous peak value of frequency-weighted acceleration; Crest Factor ─ Peak value/RMS; VDV ─ Vibration dose value; X: Fore and aft axis; Y: Lateral axis; Z: Vertical axis; Partial-A(8): the 8-hour equivalent of RMS accelerations for each machinery type.

Table 3. Two typical farming examples of daily exposure summaries.

Example	Vehicle	Ride #	Duration (minutes)	RMS (m/s^2)			VDV (m/s$^{1.75}$)			Partial-A(8) (m/s^2)			Partial VDV (m/s$^{1.75}$)		
				X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
Livestock Ranch Day	Pickup truck	1	23	0.32	0.39	0.57	3.33	4.25	9.74	0.19	0.19	0.18	7.15	6.13	11.58
Daily A(8) = 0.19 m/s^2; Daily VDV=11.58 m/s$^{1.75}$	Quad bike	2	15	0.67	0.58	0.76	7.06	5.73	9.74						
Grain Farm Work Day	Quad bike	1	76	0.51	0.51	0.74	8.23	7.68	11.49	0.65	0.76	1.13	8.30	7.97	12.34
	Tractor	2	29	0.27	0.39	0.46	2.80	4.11	6.99						
Daily A(8) = 1.13 m/s^2 Daily VDV = 12.34 m/s$^{1.75}$	Pickup truck	3	31	0.21	0.28	0.46	2.38	3.42	5.61						
	Pickup truck	4	28	0.22	0.30	0.55	2.86	3.45	7.11						

Note: # number; A(8): 8-hour equivalent value of the frequency-weighted RMS acceleration. RMS ─ Frequency weighted root-mean-squared acceleration; VDV ─ Vibration dose value; X: Fore and aft axis; Y: Lateral axis; Z: Vertical axis; Partial-A(8): the 8-hour equivalent of RMS accelerations for each axis.

Figure 3. Different whole body vibration onsite measurement cases. Figure a) the whole body vibration measurement on the seat inside a tractor cab: the seat pad set up on the surface (arrow) and data recorder safely stored in the onsite pouch behind it (arrow); Figure b) the same set-up (arrow) on an all-terrain vehicle, the data recorder was stored in a pelican case (arrow); Figure c) a measurement (arrow) made on a tractor seat without a cab; Figure d) the onsite pouch (arrow) was placed closest to the seat.

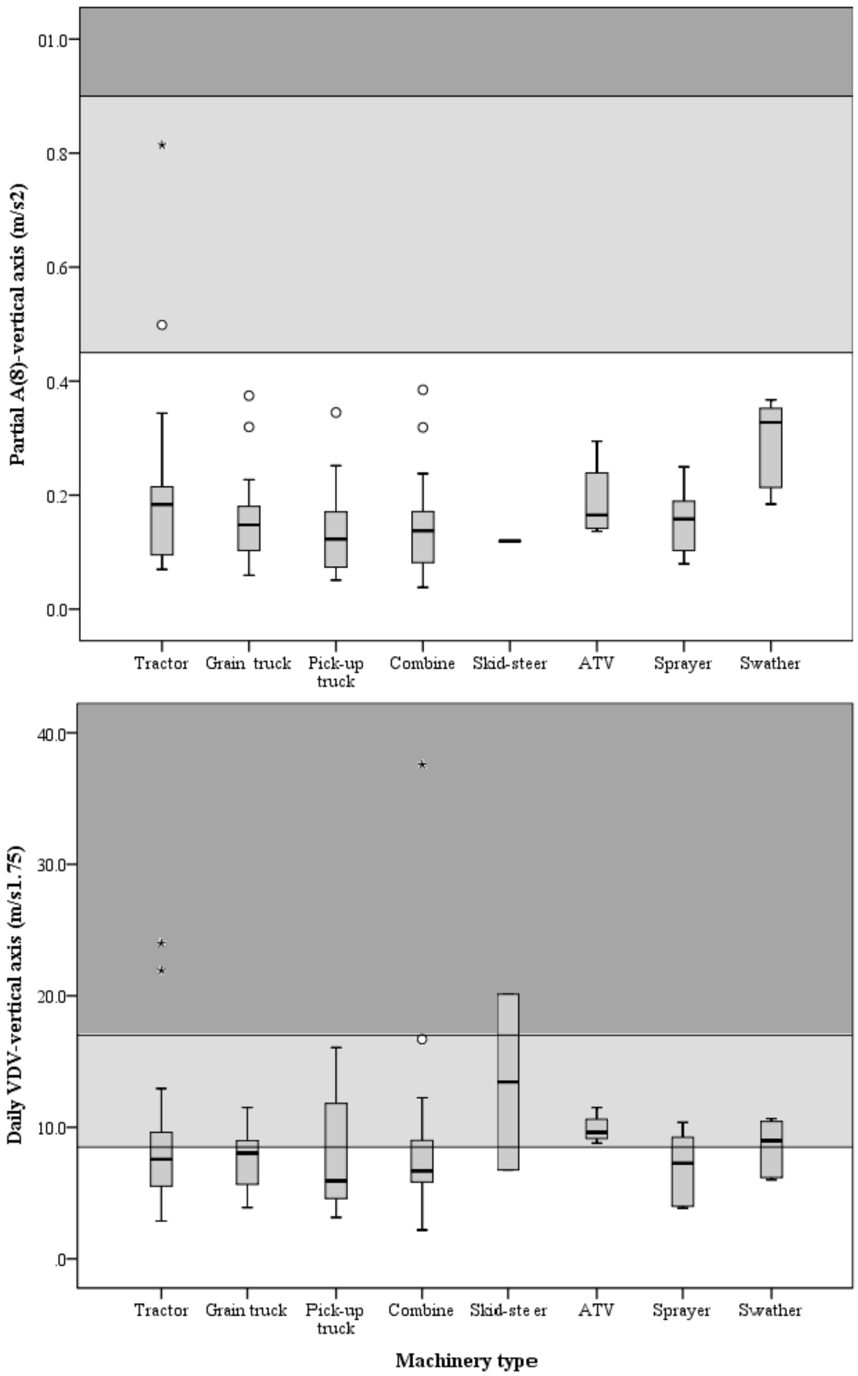

Figure 4. Boxplots of daily exposure estimates categorized by machinery type: frequency-weighted RMS acceleration (Top), vibration dose value (Bottom). *Note:* The box represents the interquartile range (25% to 75%). Circles and stars are outliers and extreme values, respectively. Lower and upper bounds reflect the health guidance caution zone published by the ISO 2631-1. The white represents a low or unclear risk. The intermediate and dark greys show that health risk is likely to exist.

Chapter 3: Manuscript2

Predicting whole body vibration exposure in Canadian Prairie farmers

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Target Journal: The Annals of Occupational Hygiene

3.1 Abstract

Objectives: The objective of this study was to use farm, vehicle, and task characteristics to predict directly-measured whole body vibration exposures in Canadian Prairie farmers.

Methods: Forty farmers from 21 farms participated in the study with a total of 87 measurements on 69 different agricultural machines. Vehicle characteristics were gathered through on-site observations. Farm characteristics and farmer's self-reported whole body vibration levels were documented via questionnaires. Whole body vibration was measured on the seat surface and summarized into root-mean-squared accelerations (RMS) and vibration dose values (VDV) per ISO 2631-1. Variables with *p-values* less than 0.2 in bivariate analyses were retained for multivariate analysis. A manual backward elimination method was conducted to build mixed-effects models for both RMS and VDV outcomes.

Results: The fixed effects of 'horsepower', 'vehicle transmission type', 'farm size', and 'farm commodity' explained 44% of the variance in RMS; fixed effects of 'horsepower', 'seat suspension type', 'loading frequency', 'tire tread type', 'jerk/jolt frequency', 'seat bottom-out frequency', 'farm commodity', and 'farm size' explained 20% of the variance in VDV.

Conclusions: Although VDV is relatively difficult to predict via vehicle and farm characteristics collected in the present study, RMS can be predicted to a moderately useful degree. Predictors identified via future modelling could allow for cost-efficient exposure assessment and a better understanding of how whole body vibration exposure is modified allowing for the development and initiation of future interventions.

Keywords: exposure assessment, prediction modeling, great plains, agriculture, mechanical shock, farm equipment

3.2 Introduction

Along with awkward or static postures, heavy lifting, and forceful movements, whole body vibration is a significant ergonomic hazard associated with low back disorders in the occupational environment [83]. Workplace mobile vehicles/machines/equipment generate vibrations that are transmitted to the human body through the seat [39]. It is estimated that nearly 3.5 million workers are exposed to whole body vibration per day in the USA [84], and 9 million workers are exposed to whole body vibration per week in the Great Britain [85]. Whole body vibration is associated with low back disorders [86] and may contribute to workplace time loss [87]; however, limited direct exposure measurements, lack of knowledge, and low public awareness may contribute to an under-recognition of both WBV level and the total population at risk [87].

Common workplace whole body vibration assessment methods have both advantages and disadvantages. The ‘gold standard’ direct measurement method is documented by the International Organization for Standardization (ISO 2631-1) [38], and used in whole body vibration studies to obtain precise vibration magnitudes in industrial sectors such as mining [88-90], quarrying [91], forestry [92], construction [93], and agriculture [94, 95]. This method involves a tri-axial accelerometer embedded in a rubber seat pad, a data logger recording at a high sampling rate and a battery power source. Measurements needed to be made at the seat surface of each machine and conducted onsite by trained investigators. The collection is complex and costly in terms of equipment and labour [96]. As a cheaper and more efficient alternative, worker self-reported whole body vibration duration has also been used as a surrogate of direct assessment in studies on large populations [84, 85, 97]; where workers are asked questions on the hours of exposure to whole body vibration in the past day/week/month/year. Such reports have been found to be inaccurate and may have recall bias. For example, McCallig *et al.* noted a large overestimation of self-reported whole body vibration hours on a questionnaire compared to face-to-face interviews or field observations [55].

Agricultural workers have high whole body vibration exposures [94, 98] due to the frequent use of machinery and also have high lifetime prevalence rates of low back disorders (LBDs) [15]. Despite the importance of this issue, assessing on-farm whole body vibration and its relation to LBDs remains challenging due to the inconvenience and expense of data collection in rural agricultural areas. Prediction modeling [99] is an alternative exposure assessment method that estimates directly-measured exposures based on characteristics that can be observed or reported via questionnaire. It has been proposed as a cost-efficient way to estimate occupational exposures from direct measures using cheaper predictors. Previously, whole body vibration modeling studies have focused on the transportation sector, including professional taxi drivers [100] and truck drivers [101, 102], and on mixed heavy industries (construction, forestry, transportation, warehousing, and wood and paper products) [103]. Only one study has modelled agricultural exposure to whole body vibration during quad bike use [104].

Greater focus on whole body vibration exposure assessments in agriculture is needed. Attention should be paid not only to vibration levels but also to the vehicle characteristics that produce the vibration and the farm where the vehicle operates. Predictors identified via modeling could allow for cost-efficient exposure assessment that may support future epidemiological research on vibration as a risk factor for the low back disorder, as well as demonstrate how whole body vibration exposure is modified by various task and vehicle characteristics to allow for tailored interventions. The objective of this study was to use farm, vehicle, and task characteristics to predict directly-measured whole body vibration exposures in Saskatchewan farmers.

3.3 Materials and Methods

3.3.1 Study Population

This investigation was carried out as part of the Saskatchewan Farmer Back Study [105]. Detailed information on study design and whole body vibration measurement protocol has been reported elsewhere (*Zeng et al., in preparation*). In brief, participants were 40 male farm workers from 21 central Saskatchewan farms. Over a one-year period, three visits per farm were conducted to measure vibration exposure during regular driving-related tasks over a range of seasons. The study protocol was approved by the University of Saskatchewan Research Ethics Board, and informed consent was obtained from all participants.

3.3.2 Whole body vibration measurements

Direct whole body vibration measurements were made on the seat of each farm machine in accordance with ISO 2631-1 standards[38]. The vibration was measured in fore and aft (x-), lateral (y-), and vertical (z-) axes. As per the measurement standards, a factor of 1.4 was applied to x- and y- axes to calculate vibration vector sum value regarding health effect at the seated position. Frequency-weighted vibration results of root-mean-squared (RMS) acceleration and vibration dose value (VDV) were obtained using the Vibration Analysis Toolset software (VATs 3.4.4, NexGen Ergonomics, Montreal, CA) per ISO 2631-1[38].

Eighty-seven measurements were gathered from 69 different machines belonging to 8 categories. The largest number of measurements were from tractors (n=26), followed by combines (n=17), pick-up trucks (n=14), and grain trucks (n=13). Fewer measurements were from high-clearance sprayers (n=6), swathers (n=5), all-terrain vehicles (ATV) (n=4), and skid steers (n=2). The average measurement duration was 85 minutes (SD 84.65, range 6-285). The average vector sums of RMS and VDV were 0.78 m/s² (SD 0.34, range 0.31-2.34 m/s²) and 10.02 $m/s^{1.75}$ (SD 5.27, range 3.66-38.58 $m/s^{1.75}$), respectively. (*Zeng et al.*, *in preparation*).

3.3.3 Potential predictor variables

For each of the 87 measurements collected, farm-level information was gathered via questionnaires from farm operators; these characteristics included 'farm commodity (grain/mixed/animal)' and 'farm size' in acres. Self-reported farmer-level personal information data were obtained from 26 out of 40 participants including 'age' (years), 'height' (cm) and 'weight'(kg). Vehicle-level information was recorded by trained researchers through observations and face-to-face interviews with farmers using the equipment; these characteristics were 'year of the vehicle', 'make and model', 'operational hours', 'odometer readings (distance)' (km), 'seat suspension (rigid/spring/air/pneumatic/hydraulic)', 'armrest (yes/no)', 'seat cushion (yes/no)', 'backrest (yes/no)', 'addition cushion (yes/no)', ' load-pulling frequency (always/never/mixed)', 'load location' (in front of the cab/behind the cab/ under the cab)', 'load type (name of implement)', 'tire type (wheel/track)', 'tread type (slick/heavy)', 'tire radius', 'drive (2-/4-/front-/all- wheel drive)', 'transmission (automatic/manual/power shift/hydrostatic)', 'number of gears', 'power steering (yes/no)', 'horsepower', and 'gross vehicle weight'(kg).

At the end of the measurement, farmers were asked to report the level of vibration exposure they perceived they were exposed to on a scale of 0–10, where 0 shows 'no vibration' and 10 represents 'unable to stay on seat'. They were also asked about their experience in terms of discomfort and jolts as per a WBV questionnaire used in a Japanese Study [106]: 1) '*Did you experience discomfort while operating your vehicle or machinery*?' (yes/no); 2) '*How often did you experience your vehicle/machinery jerk or jolt so much that you are lifted up out of your seat*?' (never/less than 5 times a day/more than 5 times a day but less than 5 times an hour/more than 5 times an hour but less than 5 times a minute/more than 5 times a minute); 3) '*How often did your seat bottom out while you are driving*?' (never/less than 5 times a day/more than 5 times a day but less than 5 times an hour/more than 5 times an hour but less than 5 times a minute/more than 5 times a minute).

3.3.4 Statistical analysis

SPSS 23.0 (IBM Inc., Armonk, NY, USA) was used for descriptive and bivariate analysis. Shapiro-Wilk normality test of normality [107] was performed on continuous variables of 'distance', 'operational hours', 'gross vehicle weight', ' horsepower', 'RMS sum', and 'VDV sum', as well as the outcome measures of RMS and VDV. RMS and VDV were found to be strongly and significantly right-skewed, and so were log transformed, which yielded normal distributions. Other non-normal variables of 'distance', 'operational hours', and 'gross vehicle weight' were grouped into four categories by quartiles. Descriptive results for continuous variables were presented as median, interquartile range (IQR), and percentiles. Bivariate and multivariate analyses were performed on the natural log-transformed vector sums of RMS and VDV.

Given that mechanical shocks have been shown to be a significant contributor to vibration exposure in farming on the Canadian prairies (*Zeng et al., in preparation*) and VDV is more representative of mechanical shocks than RMS[38], models were built for VDV, as well as the more typical RMS. Simple linear regression was conducted, and predictor variables with *P*-values less than 0.2 were considered eligible for further modeling. Spearman correlation tests[107] were performed on the remaining 'candidate' variables, and where pairs of predictors had a correlation coefficient larger than 0.6, one was eliminated. Variables were retained for further multivariate analysis if they had a minimum of missing values in the dataset, and were deemed to involve simple, low-cost data collection [96].

Prediction models were constructed using SAS 9.4 (SAS Institute Inc., Cary, NC, USA) *Proc Mixed* procedure with restricted maximum likelihood (REML). Whole body vibration measurements were nested by farmers within farms, where ‘farmer’ and ‘farm’ were random effect terms in the model. Baseline models were built with all candidate predictors as fixed effects. Subsequent models were fitted by manual backward stepwise method [108], via eliminating the fixed effect with the highest *P-value* one at a time fixed from the previous model. Model performance was assessed on several indicators: the Akaike Information Criterion (AIC), the Bayesian Information Criterion (BIC), and the R^2 values between model predictions and actual measures [109]. Final models were selected on a basis of smaller AIC and BIC, higher R^2 square, as well as consideration to model parsimony.

3.4 Results

Table 4 shows the descriptive results of characteristics of vehicle, farm, and self-reported whole body vibration. In the seat area, 100% of the vehicles measured had a seat cushion but no additional cushion. Almost every seat (97.7%) had a backrest. The major variability of seat features was observed in seat suspension type and armrest; two-thirds had an armrest, and more than half had a seat with air/hydraulic/pneumatic suspension, one-third with spring suspension, and the rest (10%) with a rigid, no suspension seat.

Outside the cab: over 90% of the farm machines had power-steering, two axles, wheel tires, and the load position behind the cab; 70% or so had heavy tread type tires and pulled a load sometimes; about 60% had 2-wheel drive, single tire, and large tire size (> 70 centimeters).

During the driving tasks, 32% of the farmers reported feeling discomfort, over 50% felt jerks or jolts and nearly 40% experienced the seat ‘bottoming out’. Sixty-one percent of farmers rated their exposure to whole body vibration at a lower level (0-4) compared to 39% rating a high level (5–10).

Table 5 showed the bivariate analysis results. Variables associated with lnRMS or lnVDV at a significant level of 0.2 are bolded in the table. RMS is associated at the 0.2 level with ‘distance’, ‘operational hours’, ‘gross vehicle weight’, ‘seat suspension’, ‘armrest’, ‘tire radius’, ‘vehicle year’, ‘transmission’, ‘gear’, ‘horsepower’, ‘self-reported whole body vibration’, ‘jerk/jolt frequency’, ‘seat bottom-out frequency’, ‘farm commodity’, and ‘farm size’. Among the above significant variables, high correlations were found in operational hours & vehicle year (-0.685), gross vehicle weight & horsepower (0.683), seat suspension & distance (-0.667), seat suspension & armrest (-0.626), and tire radius & armrest (-0.626). The vehicle year, horsepower, seat suspension, and tire radius were kept as fixed effects and operational hours, gross vehicle weight, distance, and armrest were removed. Self-reported characteristics were not used for the RMS model in order to preserve model parsimony. Finally, 8 variables including ‘seat suspension’, ‘tire radius’, ‘vehicle year’, ‘transmission’, ‘gear’, ‘horsepower’, ‘farm commodity’, and ‘farm size’ were entered into a multivariate process for the best-fit RMS model selection.

Only eight variables, including self-reported variables, were related to VDV at the 0.2 level; therefore, all were kept for further modeling. These variables were ‘seat suspension’, ‘pulling a load’, ‘tread type’, ‘horsepower’, ‘jerk/jolt frequency’, ‘bottom-out frequency’, ‘farm commodity’, and ‘farm size’.

Table 6 presents the two best models after going through the backward elimination step. A detailed model selection process is outlined in Appendix E. Four fixed effects of ‘horsepower’, ‘transmission type’, ‘farm size’, and ‘farm commodity’ explained 44.34% of the variance of directly-measured RMS. Higher RMS was observed in vehicles with lower horsepower and manual transmission at farms with smaller size and animal commodity.

Eight fixed effects of ‘horsepower’, ‘seat suspension type’, ‘loading frequency’, ‘tire tread type’, ‘jerk/jolt frequency’, ‘seat bottom-out frequency’, ‘farm commodity’, and ‘farm size’ explained 20% of the variance of directly-measured VDV. Similar to lnRMS, higher lnVDV was associated with lower horsepower, smaller farm, and animal commodity; moreover, it was related to vehicles that *always* pulled a load, had rigid seat suspension, as well as heavy tire tread. Higher lnVDV was additionally related to a farmer reporting a high frequency of the seat ‘bottoming out’.

3.5 Discussion

3.5.1 Summary of results

Forty-four percent of the log-transformed RMS variance could be predicted by the observed vehicle and farm features. Twenty percent of the log-transformed VDV could be predicted by observations and self-reported variables. Vehicle level predictors were horsepower, transmission, tire tread type, seat suspension, and loading frequency. Farm level predictors were commodity and size. Self-reported level predictors were the frequency of jerk/jolts and seat bottoming out.

The R^2 for VDV was lower than for RMS, which indicated VDV was less precisely predicted using the vehicle, farm, and self-reported characteristics in the present study. For the final model on RMS, proportions of variance explained were 20% at the farm level, 15% at the farmer level, and 65% at whole body vibration measurement level. For the final model on VDV, proportions of variance explained were 36% at the farm level, 8% at the farmer level, and 56% at whole body vibration measurements. The variance distribution showed that RMS and VDV variance were both affected by farm and farmer characteristics. The observation that more VDV variance came from the farm may relate to the different vehicles used on each farm, or alternatively different terrain type. Variance from farmers may be associated with farmer's age, body mass index, driving experience, and driving style, which was not accounted for in the present study/analysis.

The results of the present study were consistent with Clay *et al.* [104], who also found a much lower R^2 on VDV than RMS among farming quad bike users. Clay *et al.* [104] used the farmer's age, estimated driving hours on the quad bike in the measurement day, and type of rear suspension to predict both A(8) and VDV with the variance explained in 57% and 33%, respectively. In a study of multiple heavy industries, Village *et al.* [103] used self-reported speed, industry type, and vehicle type to predict RMS vector sum and 8-hour equivalent RMS [A(8)] with up to 60% variance explained. In a study of taxi drivers, Chen *et al* [100]used average driving speed, age of the driver, professional seniority, body weight, auto manufacturer, and engine size to achieve a low relative prediction error of 11% for daily vibration dose (the proportion of variance explained was not included in the Chen study). Nitti *et al.* [101] used road roughness, load, suspension, and driving speed to fit the weighted RMS acceleration in Z-axis, with an adjusted R^2 up to 90.37%.

Cann *et al.* [102] fitted regression analysis for RMS in three axes as well as vector sums using predictors of road condition (rough), truck type (cab-over design), driver experience, seat type, and truck mileage, the best fit model were from RMS vector sum with R^2 of 53%. Except for Nitti *et al.* [101] and Cann *et al.* [102] using a conventional multiple regression method, the rest of the prior studies performed mixed effects modeling[100, 103, 104], consistent with the present study.

The exposure prediction models in this study predicted whole body vibration outcomes at a low to moderate level from vehicle and farm features. Model performance may increase when adding predictors from the individual level such as farmers' height, weight, age or driving years and at the farm level such as terrain type. Rehn *et al.* [110] identified variations of whole body vibration on 7 forestry forwarders driving on 10 different terrain types; they found under the 'no load' condition, the summed RMS varied significantly by vehicle and terrain type, while under load the summed VDV varied by vehicle type as well as the operator's driving skills.

Previously, research has also been conducted in controlled contexts to explore how different vehicle designs affect whole body vibration exposure. Blood *et al.* [111] investigated Z-axis WBV under similar driving speed and road conditions, showing that trucks with cabs over the front axle had an average vibration level higher than a truck with cab behind the front axle. Marcotte *et al.* [112] tested the transmissibility of a pneumatic suspension seat and confirmed the effectiveness of attenuating vibration under the use of pneumatic suspension seat. Mayton *et al.* made a comparison of whole body vibration measurements on haul trucks and front-end loaders during different speed and load conditions; they found that RMS increased with the increasing speed and decreased with the increasing load capacity.

3.5.2 Strengths and limitations

This study has several notable strengths. We used precise whole body vibration measurements conducted along with wide range of predictors collected on vehicle-level, farm level, and self-reports. A range of farm machines from 25 different brands was measured. For each measurement, a total of 27 variables provided a broad variety of potential predictors. These features took into account aspects of the seat area (5 variables), vehicle type (1 variable), vehicle age (3 variables), vehicle design (2 variable), load (2 variables), tire (4 variables), engine (5 variables), and self-reported evaluations (5 variables). Two types of vibration metrics were used to capture both constant vibration and shocks. All data collection of direct vibration measurements were conducted by trained researchers.

In the final prediction models, some predictors at the vehicle and farm levels are novel, such as vehicle transmission and horsepower, farm commodity and size, that are also easier to obtain than direct vibration measures.

Missing values in some of the vehicle characteristics existed but were considered acceptable. Depending on the vehicle type, ‘Distance’ and ‘operational hours’ were used to describe vehicle mileage; it was collected as either one or the other. Agricultural vehicles were more likely to show hours of working than miles of driving on the dashboard. Except for these two variables, other missing data accounted for less than 10 percent of the whole dataset, mostly from not-applicable cases. For example, two tractors measured in the study had track tires, so tire radius was not applicable.

The main limitation of the present study is the inability to measure some important predictors. With such variability in the farming environment, terrain type and speed levels may play an important role in understanding vibration, though most farm machines need to be operated at a low speed and speed in farming might not differ much. We were also not able to use farmer’s age and weight as predictors due to large numbers of missing data points. The load type was too variable to be combined in a meaningful way and therefore was not included in the bivariate analysis. Agricultural machines were observed to pull different loads including, cultivator, mower, roller, trailer, grain bin, front loader, air seeder, driller, boom sprayer, manure spreader, *etc.* after the tractor in this study. Future studies may assess how different load types affect vibration level.

3.5.3 Applications and future directions

This study investigated an array of predictors for whole body vibration observed within agriculture on the Canadian prairies that provide possible occupational health intervention points for farmers. Overall, newer and larger equipment is associated with lower exposure to vibrations, likely due to better suspension, engine, and transmission systems. Replacing old equipment with new would be an effective (albeit costly) way to reduce exposure. More practically, replacing the rigid/spring suspension seat with air suspension would likely mitigate the amount of vibration or shocks transmitted to the body. The prediction model indicates that vibration assessment in agriculture could be achieved by readily evaluated and surveyed predictors at all three levels of the vehicle, farmer, and farm, at least for RMS. However, the fact that whole body vibration exposure in farming contains high shocks may require future research on prediction modelling for mechanical shock (i.e. VDV). Factors that affect whole body vibration in farming are complex, and therefore, further in-depth prediction modelling is needed before applying it to a large epidemiological study.

3.6 Conclusions

Our results show that although log-normalized VDV is far more difficult to predict using farm and vehicle characteristics; however, RMS can be predicted to a moderately useful degree. VDV and RMS variance observed at farm and farmer level may reflect important distinguishing characteristics such as terrain and vehicle type, farmer's age, body mass index, and driving style. Predictors identified via future modelling could allow for cost-efficient exposure assessment and a better understanding of how whole body vibration exposure is modified to allow for the development and initiation of future interventions.

Table 4. Farm, vehicle, and self-reported whole body vibration characteristics.

Characteristics	**N, Median (Interquartile range)**
Distance (km)	27, 168,763 (92470 - 300,000)
Operational hours (h)	53, 2372 (708 - 5080)
Gross vehicle weight (kg)	87, 9625 (4173 - 16100)
Horsepower (hp)	87, 250 (150 -350)
Characteristics	**N (Percentage)**
Farm commodity	
-Grain	15 (71.4)
-Mixed	4 (19.0)
-Animal	2 (9.6)
Farm size	
-Small (<5000 acres)	14(66.7)
-Medium (5000 -10000 acres)	5(23.8)
-Large (>10000 acres)	2 (9.5)
Seat suspension	
-Rigid	10 (11.5)
-Spring	27 (31.0)
-Air/hydraulic	50 (57.5)
Seat cushion	
-Yes	87 (100)
Additional cushion	
-No	87 (100)
Armrest	
-Yes	57 (65.5)
-No	30 (34.5)
Backrest	
-Yes	85 (97.7)
-No	2 (2.3)
Axels	
-2	80 (92.0)
-3	7 (8.0)
Pulling a load	
-Always	32 (37.2)
-Mixed	35 (40.7)
-Never	20 (22.1)
Load position	
-Front	8 (9.6)
-Behind	74 (89.2)
-Both front and behind	1 (1.2)
Tire type	
-Wheel	85 (97.7)

-Track	2 (2.3)
Tread type	
-Heavy	68 (78.2)
-Slick	19 (21.8)
Dual tire	
-Yes	31 (35.6)
-No	56 (64.4)
Tire Radius (cm)	
-Small (≤ 70)	37 (43.5)
-Large (> 70)	48 (56.5)
Vehicle year	
- ≤ 1985	20 (23.3)
- 1985-2006	36 41.9)
>2006	30 (34.9)
Vehicle type	
-Tractor	26 (29.9)
-Grain truck	13 (14.9)
-Pickup truck	14 (16.1)
-Combine	17 19.5)
-High-clearance sprayer	6 (6.9)
-Swather	5 (5.7)
-Others	6 (6.9)
Drive (2WD)	
-Yes	52 (61.2)
-No	33 (38.8)
Power steering	
-Yes	82 (94.3)
-No	5 (5.7)
Transmission	
-Manual	21 (24.1)
-Automatic	21 (24.1)
-Power shift	18 (20.7)
-Hydrostatic	27 (31.0)
Gear	
- < 5	37 (45.7)
- ≥ 5	44 (54.3)
Self-reported whole body vibration	
- 0-4	53 (60.9)
- 5-10	34 (39.1)
Jerk/jolt frequency	
- Never	39 (44.8)
- ≤ 5 times/day	35 (40.2)

- More than 5 times/day,	10 (11.5)
- less than 5 times/hour	
- More than 5 times/hour,	3(3.4)
- less than 5 times/minute	
Bottom out frequency	
- Never	52 (59.8)
- ≤ 5 times/day	25 (28.7)
- More than 5 times/day,	8 (9.2)
- less than 5 times/hour	
- More than 5 times/hour,	2 (2.3)
- less than 5 times/minute	
Discomfort driving	
- Yes	28 (32.2)
- No	59 (67.8)

Table 5. Bivariate analysis of potential predictors and whole body vibration outcome.

Variables	ln (RMS)				ln (VDV)			
	β	95% CI	R^2	*P*-value	β	95% CI	R^2	*P*-value
Distance (km)	**-0.13**	**(-0.24, -0.02)**	**0.20**	**0.02***	-0.06	(-0.22, 0.10)	0.02	0.46
Operational hours (h)	**0.19**	**(-0.03, 0.40)**	**0.06**	**0.09***	0.05	(-0.21, 0.30)	0.003	0.72
Gross vehicle weight (kg)	**-0.12**	**(-0.19, -0.04)**	**0.11**	**0.002***	-0.05	(-0.14, 0.03)	0.02	0.21
Seat suspension	**0.24**	**(0.13, 0.36)**	**0.18**	**<0.001***	**0.10**	**(-0.03, 0.24)**	**0.03**	**0.13***
Armrest	**-0.27**	**(-0.44, -0.10)**	**0.10**	**0.002***	-0.05	(-0.25, 0.15)	0.003	0.61
Pulling a load	0.01	(-0.10, 0.13)	0.001	0.83	**-0.08**	**(-0.21, 0.04)**	**0.02**	**0.20***
Load position	-0.05	(-0.32, 0.23)	0.001	0.75	-0.01	(-0.32, 0.29)	0.000	0.94
Tire radius (cm)	**-0.21**	**(-0.38, -0.04)**	**0.07**	**0.015***	-0.01	(-0.20, 0.19)	0.000	0.93
Tread type	-0.08	(-0.28, 0.13)	0.006	0.47	**-0.18**	**(-0.41, 0.04)**	**0.03**	**0.11***
Dual tire	0.05	(-0.14, 0.22)	0.003	0.62	-0.01	(-0.21, 0.19)	0.000	0.93
Vehicle year	**-0.21**	**(-0.31, -0.10)**	**0.15**	**<0.001***	-0.08	(-0.21, 0.05)	0.02	0.21
Vehicle type	-0.03	(-0.07, 0.02)	0.015	0.26	-0.01	(-0.06, 0.04)	0.002	0.68
Drive	-0.07	(-0.25, 0.11)	0.008	0.41	-0.12	(-0.32, 0.07)	0.02	0.21
Transmission	**-0.15**	**(-0.22, -0.09)**	**0.19**	**<0.001***	-0.03	(-0.11, 0.05)	0.005	0.50
Gear	**0.18**	**(0.00, 0.36)**	**0.05**	**0.045***	0.04	(-0.16, 0.24)	0.002	0.70
Horsepower (hp)	**-0.001**	**(-0.002, -0.001)**	**0.224**	**<0.001***	**-0.001**	**(-0.001, 0.00)**	**0.04**	**0.053***
Self-reported whole body vibration	**0.13**	**(-0.04, 0.31)**	**0.03**	**0.13***	0.04	(-0.16, 0.23)	0.002	0.71
Jerk/jolt frequency	**0.19**	**(0.09, 0.29)**	**0.14**	**<0.001***	**0.14**	**(0.03, 0.26)**	**0.07**	**0.017***
Bottom out frequency	**0.22**	**(0.12, 0.33)**	**0.18**	**<0.001***	**0.17**	**(0.05, 0.29)**	**0.09**	**0.005***
Discomfort driving	0.04	(-0.14, 0.23)	0.002	0.66	0.12	(-0.08, 0.32)	0.02	0.23
Farm commodity	**0.24**	**(0.11, 0.37)**	**0.13**	**0.001***	**0.2**	**(0.05, 0.35)**	**0.08**	**0.009***
Farm size	**0.17**	**(-0.29, -0.04)**	**0.08**	**0.009***	**-0.14**	**(-0.28, 0.01)**	**0.04**	**0.058***

Note: ln (RMS): natural log-transformed root-mean-square accelerations; ln (VDV): natural log-transformed vibration dose value; * *P-values* less than 0.2 are considered for future models.

Table 6. Vehicle characteristics and self-reported whole body vibration associated with direct measured RMS and VDV in final mixed-effect models, the farmer and farm as random effects.

Variables	RMS vector sum		VDV vector sum	
	Coefficient	*P-value*	Coefficient	*P-value*
Intercept	0.128	0.523	2.398	<0.001*
Horsepower	-0.001	<0.001*	<-0.001	0.604
Farm size	-0.083	0.273	-0.139	0.245
Transmission: manual	0.376	<0.001*		
Transmission: power shift	0.368	<0.001*		
Transmission: automatic	0.311	0.003*		
Transmission: hydrostatic	Ref(0)			
Farm commodity: grain	-0.346	0.076	-0.200	
Farm commodity: mixed	-0.247	0.271	-0.013	
Farm commodity: animal	Ref(0)	0.523	Ref(0)	
Suspension: air			-0.106	0.507
Suspension: spring			-0.009	0.960
Suspension: rigid			Ref(0)	
Pulling a load: always			0.235	0.106
Pulling a load: mixed			0.158	0.269
Pulling a load: never			Ref(0)	
Tire tread type: heavy			0.064	0.619
Tire tread type: slick			Ref(0)	
Jerk or jolt frequency			0.024	0.732
Seat bottom out frequency			0.159	0.040*
R^2	44.34%		19.91%	

Note: * *P-value* less than 0.05.

Chapter 4: Discussion

4.1 Summary of results

In this thesis, 87 WBV measurements were gathered on 8 different machine types that included tractors, combines, pick-up trucks, grain trucks, sprayers, swathers, ATVs, and skid steers. Results from the present study revealed a WBV exposure profile of Saskatchewan farmers that includes moderately high constant vibrations and high mechanical shocks. Over 97% of vector summated crest factors were above 9, indicating VDV was an appropriate metric instead of RMS according to ISO 2631-1(1997) [38]. The greatest vibration amplitudes were from the vertical (z) axis, with a mean dominant frequency of 4.1Hz (ranging from 2.5Hz to10Hz), creating a potential risk of injury to the lumbar spine for farmers exposed during seated posture.

Vehicle, farmer, and farm level characteristics may affect vibration magnitudes. The mixed-effect models built in this study were developed to describe potential sources of WBV variance using predictors. Although VDV is a more appropriate metric for vibration context in this study, it was found to be difficult to predict with variables collected in this study. Only 20 percent of the variance in the log-transformed VDV was explained by fixed effects of ‘horsepower’, ‘seat suspension type’, ‘loading frequency’, ‘tire tread type’, ‘jerk/jolt frequency’, ‘seat bottoming out frequency’, ‘farm commodity’, and ‘farm size’. Meanwhile, 44% of the variance in log-transformed RMS was explained by fixed effects of ‘horsepower’, ‘vehicle transmission type’, ‘farm size’, and ‘farm commodity'.

4.2 Comparison to other results and positioning this new knowledge in the area

Manuscript 1 described the WBV exposure patterns of common machinery employed on the Canadian Prairies of Saskatchewan. Prior to the current work, little research has been conducted on agricultural WBV exposure on the Great Plains of North America. Previous farming studies have assessed exposure to WBV in New Zealand [69], Finland [70], Japan [71, 72], and Poland [79, 98]. The results of the present study will add the WBV exposure profile of Canadian Prairie farmers into this global literature.

In the present study, the range of RMS vector sum was from 0.31 m/s² to 2.34 m/s², similar to Futatsuka *et al.* 's findings on agricultural machinery use which ranged from 0.35 m/s² to 1.63 m/s² [79]. The maximum value in the present study (2.34 m/s²) is much higher than previously reported (1.66 m/s²) [79], which may be due to the high vibration magnitudes from the ATV measurements. Futatsuka *et al.* did not consider metrics for VDV and crest factor [79]. Futatsuka *et al.* [79] measured whole body vibrations on 10 commonly used agricultural machines in 7 categories in Japan in the 1990s, such as combine, tractor, transplanter, carrier, and cultivator. One participant performed four experimental rides on each machine, about 30s per ride. In this Japanese study, the Z-axis was not the dominant vibration source of the vector sum; instead similar vibration magnitudes were observed from x-, y-, and z- axis. The RMS vector sum range in the present study was wider than Futatsuka *et al.* 's findings, which may be due to measurements obtained from the wider variety of 'real farming' conditions including different participants, tasks, terrains, and weather.

With respect to the tractor-based measurements in this study, tasks such as lawn mowing and cultivating were observed to have the highest measured vibration while the lowest was from transportation tasks. These findings were also consistent with previous research. Solecki [73] measured whole body vibration in 30 different agricultural activities among private farmers.

All measurements were conducted on 12 tractors from 15 farms with cultivated land more than 25 acres. The highest frequency weighted accelerations were from the vertical direction. Solecki also observed high crest factors (i.e. above 9). Activities including spraying fertilizers, aggregating soil, mowing grass, and swathing hay had considerably high RMS vector sums (range 0.87 - 1.78 m/s^2); but low values were observed from transporting on field roads, seeding, harvesting, and digging tasks (range: 0.25 - 0.58 m/s^2). However, the author did not report the measurement duration of each activity, and there were no VDV calculations.

Manuscript 2 studied the predictors of whole body vibration exposure in the farming context of the Canadian prairies. In this study, the best RMS model predicted 44% of the measured variance, and VDV model predicted 20%; to our knowledge, these are the first exposure prediction models constructed for Canadian agriculture. These results will add more information regarding potential predictors of agricultural whole body vibration exposure to the world literature. From the previous literature, only one agricultural modeling study from Clay *et al.* [104] was found investigating whole body vibration exposure in farmers from New Zealand.

The results of the present study were consistent with Clay *et al.* [104], who also found a much lower R^2 from the VDV model (33%) than the RMS model (57%) among farming quad bike users. As pointed out by Clay *et al.* [104], VDV is more difficult to predict than RMS. The VDV calculation has an integrated time factor; it refers to the cumulative vibration level that also emphasizes mechanical shocks. During real driving conditions, RMS is a constant vibration generated steadily, while VDV is more associated with an uneven driving surface and bumps/jolts. It is logically more difficult to predict the transient nature of shocks when they show up in the dataset.

Exposure modeling from other industries has focused on the vibration metric of frequency-weighted RMS accelerations. The present study used vehicle horsepower, vehicle transmission, farm commodity, and farm size to predict RMS vector sum with the R^2 of 44%, which is lower than other studies. In a study of multiple heavy industries, Village *et al.* [103] used self-reported speed, industry type, and vehicle type to predict RMS vector sum and 8-hour equivalent RMS [A(8)] with up to 60% variance explained. In a study of taxi drivers, Chen *et al.* [100] used average driving speed, age of the driver, professional seniority, body weight, auto manufacturer, and engine size to achieve a low relative prediction error of 11%. for daily vibration dose (the proportion of variance explained was not included in the Chen study). Nitti *et al.* [101] used road roughness, load, suspension, and driving speed to fit the weighted RMS acceleration in Z-axis, with an adjusted R^2 up to 90.37%. Cann *et al.* [102] fitted regression analysis for RMS in three axes as well as vector sums using predictors of road condition (rough), truck type (cab-over design), driver experience, seat type, and truck mileage, the best fit model were from RMS vector sum with R^2 of 53%.

The lower RMS model fit in the present study (44%) may be due to the diversity in the dataset. We measured 69 different machines in 25 brands performed by 40 male workers on 21 different farms. The model fit might increase if some potential predictors were collected and used, such as farmer’s age and weight, the terrain condition, and the driving speed.

4.3 Methodological Considerations

4.3.1 Farm, farmer, and whole body vibration measurement sampling strategy

Convenience sampling was used in this study to obtain the targeted 21 farms and 40 farmers. Sixty farms in the participating list of the Saskatchewan Farm Injury Cohort Study [78] were contacted by mailed letters. A geographic scope of 400 kilometers was set in this study for practical reasons, such as time spent on round trips to rural farms within a measurement day and data collector's safety. However, farms that are located outside the inclusion criterion area might have a different landscape with different topography, weather, soil moisture conditions, and therefore farmers may conduct farming in a different way and encounter different WBV exposures.

The farms sampled may not represent the whole Saskatchewan farming population. It is likely difficult for the twenty-one farms sampled in the current study to be representative for all 36,952 Saskatchewan farms reported from the 2010 Census of Agriculture [48]. The participation of farms and farmers were based on their interest and availability, introducing a potential selection bias. We observed a median farm size of 4000 acres (interquartile range: 1850-7120 acres), which was larger than Saskatchewan's average farm size of 1668 acres [48]. It was possible that farmer operators who managed large land properties, and also have adequate farm equipment, and enough human resources, would be more likely to say 'yes' to this type of study.

For the forty farmers enrolled in the present study, all whole body vibration measurements were made using a naturalistic setting. We showed up at the farm, followed the farmer during his/her regular work tasks, and conducted whole body vibration measurements during driving activities. In each season, farm visits were arranged between the Saskatchewan Farmers Back Team and the farm operator. Farmers' exposure to whole body vibration was assessed within this real farming context. A substantial variety of farming tasks and machinery use was observed and even measured, including seeding, spraying, maintaining, swathing, harvesting, transporting, and ranching, all during real conditions that were sometimes sunny and sometimes rainy. The seasonal variability of machinery use was captured to some degree, but may be underestimated. No WBV was measured during the winter when some on-farm activities such as snow removal and animal feeding may occur using tractors, skid steers or all-terrain vehicles. The present study may not measure every commonly-used machine model, and therefore may not be sufficient to represent the complete machinery fleet used in Saskatchewan farming.

Purposive sampling and quasi-experimental design is a strategy used in previous vibration studies. Futatsuka *et al.* chose one driver to conduct test rides for ten commonly-used agricultural machines, where whole body vibration was measured during four rides per vehicle with 30 seconds per ride at the 'normal farming speed' [72]. For the researcher, this approach was efficient and fast to target specific machines of interest for whole body vibration assessments. However, observation bias may exist, and results may be different from vibration measured in real working tasks. For example, the participant may change the driving behavior knowing himself/herself was under observation (the Hawthorne effect [113]), such as driving more carefully in the experimental tests. In the present study, the Hawthorne effect was also likely to exist. Farmers might perform driving in a different way once they knew that the machine was under measurements, though this effect might not be large because the farmers were not followed by the researcher when they were driving.

4.3.2 Whole body vibration assessment methods

In the present study, whole body vibration assessment methods followed international standards (ISO 2631-1) [38]. This is an accurate approach to measure whole body vibration magnitudes, and therefore it has been popular in agricultural vibration research [72, 73, 80, 94, 95]. This method has strict requirements about the type of instrument used (the tri-axial accelerometer, the seat pad, and the data logger) and the way assessment conducted (on the seat surface). Though complicated and costly [96], all direct measurements were collected precisely in the present study.

Regarding exposure metrics; Solecki used RMS, peak and crest factor to preliminary describe whole body vibration in the rural farming environment [73]. Later, Solecki used the 'vibration dose' calculated from RMS values and exposure duration to describe farmer's annual exposure [98]. Futatsuka *et al.* reported RMS (X-, Y-, Z-, and vector sum) and 8-hour equivalent RMS (A8) for farming machinery [72]. Sorainen *et al.* studied RMS value and its average frequency spectra in tractor driving [70]. Park *et al.* used daily equivalent RMS value from ISO 2631-1 [38] due to a crest factor less than 9 and daily equivalent static compression dose (S_{ed}) from ISO 2631-5 [82] to evaluate health risk for agricultural tractor operators [95]. Milosavljevic *et al.* also used S_{ed} to assess vibration exposure among farmers using the quad bike and on the contrary, they observed a crest factor greater than 9, and therefore VDV was further analyzed instead of RMS [114]. In this study, whole body vibration was described using RMS, peak, crest factor, and VDV per ISO 2631-1 [38].

Whole body vibration assessment in large populations where individuals have different exposure profiles typically use self-reported surveys to estimate the exposure. Palmer *et al.* investigated occupational whole body vibration exposure patterns in the Great Britain [85]. Twenty-six vehicles were listed in the questionnaire for participants to identify the exposure sources and durations in the past one week, separately for work and leisure. Information on current occupation, as well as the industry, was also collected via questionnaire. The vibration estimation of the equivalent vibration dose value (eVDV) was calculated by assigning reference frequency-weighted accelerations of each vehicle type according to British Standards (6841) [115]. Tak *et al.* estimated the total number of workers exposed to whole body vibration in their current occupation in the United States of America [116], where the workers who reported 'every day' exposure were classified into the 'exposed' population in a structured question of five scales. Tuchsen *et al.* evaluated the risk of men's disability pension using self-reported whole body vibration exposure, where the exposed group consisted of workers with more than 25 percent-working-hour vibration exposure [97]. Self-reporting whole body vibration hours is inexpensive and convenient, but subject to recall bias. McCallig *et al.* noted a large overestimation of self-report WBV hours on a questionnaire compared to face-to-face interviews or field observations [55].

In the future, electronic devices such as smartphones or similar devices could be potentially used in whole body vibration assessment at the workplace. Wolfgang *et al.* tested the accuracy of whole body vibration measurements on light vehicles using a fifth-generation iPod Touch ^{TM}, driving through different road conditions. Simultaneously, they also conducted the gold standard measurements. Results of comparison showed an absolute error of about 0.02 m/s^2 in the RMS accelerations from each axis [117]. Wolfgang *et al.* also applied the same comparison on the heavy mining equipment in surface coal mines and observed a higher absolute error of about 0.09 m/s^2 in the RMS accelerations per direction [118]. This approach allows for cheap and systematic assessment at the workplace. However, as the author pointed out, the error might be larger if the vibration magnitudes were high [117]. These two studies only tested on vibration metric of RMS. Future research may focus on testing the error of other metrics, such as VDV.

4.3.3 Exposure prediction models

The present study modelled whole body vibration exposure using predictors gathered via a vehicle information form (see Appendix B) and a daily exposure questionnaire (see Appendix C).

The data collection on vehicle characteristics was comprehensive, except for vehicle driving speed. Village *et al.*, Chen *et al.*, and Nitti *et al.* all found speed was an important predictor of whole body vibration [100, 101, 103]. Mayton *et al.* [91] also found RMS measured on haul trucks and front-end loaders increased with increasing speed.

The present study adopted new farm predictors of commodity and size which have not been used before, but which are specific to agriculture and which turned out to be moderately good predictors of lnRMS. Another farm characteristic found to be associated with vibration in the literature but not used in this study was the terrain condition. ‘Road roughness’ has been used as a significant predictor of RMS (Z-) exposure in truck drivers; Nitti *et al.* [101] classified it into two conditions of ‘provincial’ and ‘highway’. Cann *et al.* [102] also measured RMS among truck drivers but on highways only, where road conditions were classified into ‘smooth’ and ‘rough’, and found the ‘rough road’ was the greatest predictor of RMS in the study when controlling for factors of speed and season. In our study, some information on terrain conditions at the farm was gathered, though not used as a predictor due to the inability to match each ride to its driving surface. At the end of the measurement day, farmers were asked to report the percentage of driving time spent on six types of terrain surface, including ‘smooth pavement or cement’, ‘gravel’, ‘packed earth’, ‘broken, cracked, or buckled dry earth’, ‘soft earth’, ‘rough off-road (logs, rocks, ditches)’, on the daily questionnaire. Some farmers had transferred among several vehicles and some drove non-farming equipment, even within the same machine; one farmer could have driven over several terrain types. This information was a self-reported, general estimate of their day, which may have been affected by recall bias.

Other factors that haven’t been clearly measured in this study but which would likely affect whole body vibration measures are at the farmer level, such as age, weight, height, and driving experience. Age and driving experience may affect how the driver reacts on bumpy roads. Rehn *et al.* [110] discussed the variance source of VDV vector sums on the loaded forestry forwarders, which might be due to operator's driving skills. Clay *et al.* [104] found older farmer had lower vibration exposures than younger farmers. Body mass and height may affect how whole body vibration energy is transmitted to the human body in terms of frequency. The height of the participant may have a relation to how he/she adjusts the height of the seat. Marcotte *et al.* [112] found when the height of an air suspension seat was adjusted to its minimum, the vibration frequency (Z) of 2.4 Hz would be amplified which will likely contribute to driver discomfort. Body mass may have complicated interactions with other vehicle and workplace characteristics as found by Milosavljevic *et al.* [119].

In the present study, the predictor of farm commodity may partly act as a surrogate of terrain and equipment type in both final models. The current models showed lower RMS and VDV measures on grain farms. Grain farms may be more likely to have the flat terrain type than the animal farms; meanwhile, grain farms are more likely to employ larger farm equipment (e.g. tractor, combine, grain truck) while animal farms are more likely to have smaller ones (e.g. ATV, pickup truck). Farm size may act as surrogates of the year and make of vehicle, and the age of farm worker. As we observed in the present study, the equipment used on the larger farms are likely to be newer and more advanced, and the farmers who worked there tended to be younger.

4.3.4 Lessons learned

For future research on whole body vibration measurements on the Canadian prairies, there are several lessons learned which may be useful. To begin with, the naturalistic sampling setting is good for understanding a farmer's work day, though purposive sampling on various machinery may obtain a more comprehensive profile of whole body vibration exposure sources. The working hours for family farms are unique and flexible. The typical 8-hour sampling scheme may not suit agricultural workers. Therefore, workplace information regarding the total work period over 24 hours is needed. For whole body vibration measurement duration, future studies could either measure a full day's exposure or conduct several sampling measurements then extrapolate to a full working day gathered from farmers' self-reports. In Saskatchewan, agricultural whole body vibration metrics could reasonably focus only on VDV and S_{ed} due the high crest factors (above 9).

For data collection of potential predictors, future studies may not need to record comprehensive information on armrest, backrest, seat cushion, additional cushion, axles, load position, and tire type, due to low variability. Other important predictors that should be collected are the driving speed, terrain condition, farmer's age, body mass, height. The average driving speed could be calculated as the ratio of the driving distance to the measurement duration, where the former could be obtained from the odometer readings. Age, body mass, and height may be obtained from self-reports. The terrain condition is challenging, and farmers may have different understandings of it, which may need a trained researcher to drive along and make appropriate evaluations.

4.3.5 Statistical considerations

Manuscript 1 performed mean and standard deviation analysis to describe vibration metrics of RMS, peak, crest factor, and VDV. At least 5 measurements were gathered from tractors, combines, pickup trucks, grain trucks, sprayers, and swathers, which provides an exposure profile of common machines used at grain farms. Three out of four ATV measurements were from animal farms. More measurements during use of ATV and skid steer will help better determine the characteristics associated with this machinery's vibration levels among Saskatchewan farmers.

Manuscript 2 conducted descriptive analysis using median, interquartile range, and percentile, bivariate analysis using simple linear regression, and multivariate analysis using mixed-effect modelling. Over 80 whole body vibration measurements were used in the mixed models. Maas *et al.* found that in two-level models, at least 50 samples are needed for unbiased estimates in level-2 standard errors [120]. In this study, whole body vibration was measured within farmers within farms. Though three levels of data were collected, the actual modeling did not use farmer level characteristics due to high proportions of missing data. Therefore, a sample size of 80 may be sufficient for an accurate estimate.

Mixed-effect modeling was chosen instead of the generalized estimating equation (GEE) as the statistical method in this study partly due to the clustered data. GEE estimates the parameters of the generalized linear model (GLM) [121], but our vibration measurements were not independent, which violates the independent assumption of GLM. Mixed effects models were also the most common used in prior whole body vibration exposure modeling research [100, 103, 104]. Interactions were not checked in both final models based on previous literature findings [100, 119]. Age, body weight, and speed might interact with other characteristics; however, these were all not available in the current study. Previously Chen *et al.* [100] found interactions between speed and engine size, body weight and professional seniority, body weight, and age, speed and year of make. Milosavljevic *et al.* [119] investigated the vibration data from on-farm quad bike use in New Zealand, and found that farmer’s body height, rural terrain condition, and the mechanical factor of vehicle suspension confounded the relationship between body mass and 1-h VDV (Z-); there might be some complicated interaction among farmer, vehicle and farm characteristics.

4.4 Strengths and limitations

Manuscript 1 followed the gold standard measurement of whole body vibration which achieved accurate vibration magnitudes. Three seasonal visits captured the substantial seasonal variability of tasks and machines. For example, we measured farm vehicles from 25 different brands[1] over the three seasons. A limitation was the inability to measure full day exposure due to practical reasons, which led to the inability to evaluate health effects of whole body vibration using ISO 2631-5 [82] standards.

Manuscript 2 modeled direct whole body vibration measurements with predictors chosen from 27 characteristics at the vehicle and farm levels. One strength was building models for both RMS (constant vibrations) and VDV (mechanical shocks). The other strength was the use of novel and accessible predictors, such as the farm commodity and farm size, vehicle transmission and horsepower. The main limitation is the inability to use some important predictors due to missing (e.g. farmer age, body weight, and height), non-specific data collection (e.g. terrain condition), and predictors that were not measured (e.g. speed).

4.5 Relevance of research

Results from the present study provide a valuable whole body vibration exposure profile of Saskatchewan farmers and act as a foundation for future research. A stakeholder advisory group comprised of study participants (farmers), manufacturers, researchers (Farmers Back Study), occupational hygienists, and educators participated in two meetings where useful advice on data collection phases and results interpretation was obtained.

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[1] Dodge, Versatile, Volvo, Gleaner, International, Case, John Deere, Leading solution, Honda, Toyota, New Holland, Chevrolet/Chevy, Bobcat, MacDon, Massey Ferguson, Ford, Polaris, GMC, Deutz-allis, Suzuki, Kenworth, White, Freightliner, and Prairie star.

Results of the present study were compared with ISO standards [38] and European Vibration Directive workplace guidelines [39]. Though vibration is mentioned in the Saskatchewan Occupational Health and Safety Regulations, there is no specific mention of workplace monitoring or occupational limits with respect to whole body vibration. According to the Saskatchewan Occupational Health and Safety Regulations (1996) [122] section 81(1)(c), vibration is listed as a potential factor that may cause musculoskeletal injury. The Saskatchewan Employment Act (latest version effective on December 31, 2015) [123] also mentioned that regulations may be made by the Lieutenant Governor in Council about things that affect the working condition, vibration included. In keeping with this lack of legislative specificity, the impression of the author gathered from visiting 22 farms over the course of a growing season is that general awareness of whole body vibration as an occupational hazard is low.

The results of manuscript 1 showed high levels of vibration and shocks in Saskatchewan farming. Limiting the driving hours on each vehicle might be a way to stay below the levels set by the European Vibration Directive 2002/44/EC regarding the RMS metric [39]. Manuscript 2 has identified factors associated with constant vibration and shocks. The following statements are all based on analysis results from the present study. The vibration predictor with the highest immediate modifiability is the time spent on machines. The cumulative effect of vibration exposures of VDV on the human body will be reduced if regular breaks were taken since the VDV calculation integrates the time factor [38]. Though in farming, breaks are hard to arrange due to the time pressure and seasonality of work. Farmers need to finish certain seasonal tasks in limited days. The ones with medium modifiability were the vehicle. Replacing a rigid/spring seat suspension with an air/hydraulic/pneumatic one would likely reduce the amount of vibration energy transmitted into the body. Replacing old machines with new ones equipped with larger tire size, the hydrostatic transmission, higher horsepower, larger gross weight, and fewer gears would reduce the vibration experienced during driving. The predictor with low modifiability is the farm. Larger farm size with grain commodity was observed to have fewer vibration exposures compared to smaller farms with the animal commodity.

4.6 Knowledge translation plan

The Saskatchewan Farmers Back Study Team met with a stakeholder advisory group twice (before and after data collection); at the second meeting preliminary results were disseminated and discussed. All farmers who participated in the study will receive a brochure that highlights the key findings and take home messages of the study. Given the low awareness but high risk of the whole body vibration exposure, major findings will also be released through media to improve awareness rates. For the academic community, results have been and will be presented at conferences to disseminate and to call for future research, including the 2015 Saskatchewan Epidemiology Association (SEA) conference held in Regina, Saskatchewan, and 2016 Canadian Association for Research on Work and Health (CARWH) conference held in Toronto, Ontario. Manuscript 1 and 2 will also be submitted to academic journals of Ergonomics and the Annals of Occupational Hygiene, respectively.

4.7 Future directions

Due to high crest factors found in the present study, future research of whole body vibration assessment should consider both ISO 2631-1 [38] and ISO 2631-5 [82] standards for to mechanical shocks. Future research can also explore whether the application of smartphones or iPod Touch^{TM} or similar devices is appropriate and valid for agricultural whole body vibration assessment, with experimental tests on both RMS and VDV metrics. Whole body vibration field assessment would be more accessible if modern smartphone technology was proven to be effective; this would help overcome the barrier of expensive measurements, allow for regular workplace monitoring, improve the awareness of whole body vibration exposures, and promote some self-care prevention strategies.

Future exposure modeling research may focus on how a farmer's demographic characteristics (e.g. age, body mass/weight) and driving style (e.g. speed, skills, and experience) would affect their exposure to whole body vibration. The exposure models could be further tested and validated by bootstrapping samples to understand the internal validity and model generalizability.

Future epidemiological research is also needed to study musculoskeletal symptoms and associated ergonomic risk factors in the farming population. From the study sample (n=31), the musculoskeletal symptom that farmers were experiencing during the study period was found the highest at the lower back area with a prevalence of 54.84%. This was high compared to other body areas:38.71% in arms; 25.81% in the hip and thigh; 22.58% in the knee; 19.35% in the lower limb; 16.12% in thoracic spine; 16.12% in head and neck; 6.45% in abdominal and others. Specifically, the low back pain 1-week and lifetime prevalence was 40.74% and 86.21%, respectively (See Appendix F). Low back pain is caused by multiple factors; whole body vibration is a notable physical factor that seems likely to contribute substantially to low back pain in this population given the high exposures identified in the present study results. To support future cost-efficient and long-term large epidemiological study in farmers, job exposure matrices and exposure modelling are possible exposure assessments tools to consider.

4.8 Conclusion

WBV varies between machines. High exposure to constant vibration and mechanical shocks, along with the aging of the farming population, presents a substantial risk to farmer health.

Where possible, actions such as modification of vehicle design should be taken to reduce vibration exposure in the farming environment. The prediction model developed here can be used to understand the constant vibration level on the farm using predictors of horsepower, transmission, farm size, and farm commodity. Mechanical shock is more difficult to predict, which may relate to unmeasured factors such as the terrain condition and how a given farmer operates the machine. Predictors identified via modeling will help understand exposure variances and where possible interventions could be implemented. These predictors may also be new target surrogates for future whole body vibration exposure assessment in epidemiological studies.

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APPENDIX A: WBV protocol

Xiaoke Zeng led the development of the WBV protocols by working with the study team to conduct pilot tests, document procedures, and draft the following protocol document.

Farmer Back Study:

Saskatchewan Farmers Back Study

Vibration Protocol

This document describes the collection equipment, including connections, typical configuration, onsite collection protocol, and data analysis.

SAMPLING

Conduct a vibration measurement in all cases when a worker is sitting in a vehicle.

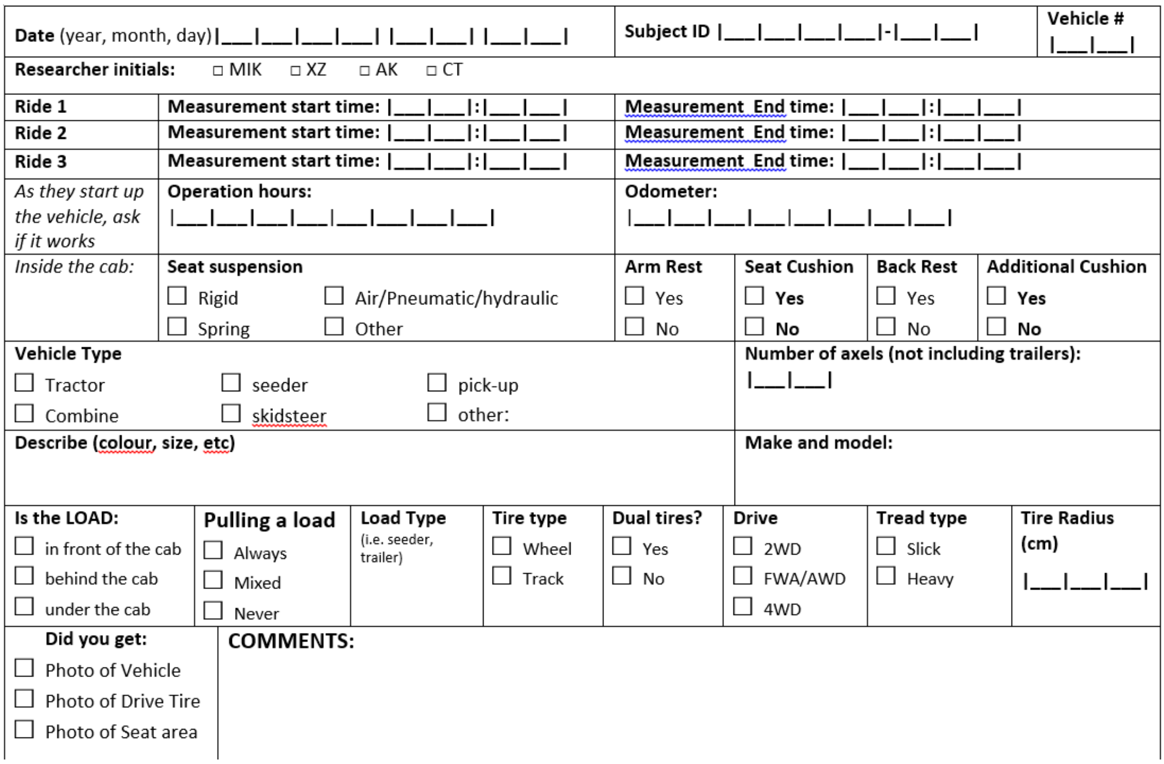
1) We will collect vibration measurements for **up to 4 hours** in a single vehicle. Get an estimate of how long the participant will spend in the vehicle/machinery for that day, and if the participant will spend longer than 4 hours, determine a course of action to retrieve the equipment.

2) We will collect vibration measurements in all vehicles/machines that a participant operates for **more than 5-10 min** during our visit. We will never try for measurements shorter than 5 min. For measurements around 10 minutes, use your judgment. If the time in the vehicle will be very short and the participant feels the measurement will be cumbersome (or too time-consuming), use your best judgment about whether to negotiate or not. If you can charm your way into it, great. If not (or your instincts say not to try), that's fine too. We'd like to continue being invited back to the farms, so we don't want to alienate anyone by being too demanding.

3) If a participant is having a 'mixed tasks' day (or a portion of their day), then you will likely to be following him/her for tablet observations when they approach the vehicle. Take a break from observations while you tape and set up the WBV equipment. If this will be a short vehicle use or they will be in the yard (in visual contact the whole time), then stay back out of the way and keep an eye out so that you can approach the vehicle and stop the measurement when they are done.

4) A 'driving' day (or a portion of the day) occurs when the participant spends an extended amount of time in a vehicle/machinery that may drive offsite. Examples include seeders, sprayers, swathers, and combines. If there is an additional seat with a seatbelt (some farm machinery will have this, as will most grain trucks and pick-up trucks), feel free to ride along if you choose. Otherwise, stay behind and catch up on paperwork/file management. **Do no**t ride along if there is no passenger seat with a **seatbelt**.

Vehicle Information Form



Date (year, month, day) |___|___|___|___| |___|___| |___|___|

Subject ID |___|___|___|___|-|___|___|

Vehicle # |___|___|

Researcher initials: □ MIK □ XZ □ AK □ CT

Ride 1	**Measurement start time:** |___|___|:|___|___|	**Measurement End time:** |___|___|:|___|___|
Ride 2	**Measurement start time:** |___|___|:|___|___|	**Measurement End time:** |___|___|:|___|___|
Ride 3	**Measurement start time:** |___|___|:|___|___|	**Measurement End time:** |___|___|:|___|___|
As they start up the vehicle, ask if it works	**Operation hours:** |___|___|___|___|___|___|___|___|	**Odometer:** |___|___|___|___|___|___|___|___|

Inside the cab:	**Seat suspension** ☐ Rigid ☐ Air/Pneumatic/hydraulic ☐ Spring ☐ Other	**Arm Rest** ☐ Yes ☐ No	**Seat Cushion** ☐ **Yes** ☐ **No**	**Back Rest** ☐ Yes ☐ No	**Additional Cushion** ☐ **Yes** ☐ **No**

Vehicle Type

☐ Tractor ☐ seeder ☐ pick-up

☐ Combine ☐ skidsteer ☐ other:

Number of axels (not including trailers): |___|___|

Describe (colour, size, etc)

Make and model:

Is the LOAD: ☐ in front of the cab ☐ behind the cab ☐ under the cab	**Pulling a load** ☐ Always ☐ Mixed ☐ Never	**Load Type** (i.e. seeder, trailer)	**Tire type** ☐ Wheel ☐ Track	**Dual tires?** ☐ Yes ☐ No	**Drive** ☐ 2WD ☐ FWA/AWD ☐ 4WD	**Tread type** ☐ Slick ☐ Heavy	**Tire Radius (cm)** |___|___|___|

Did you get:

☐ Photo of Vehicle

☐ Photo of Drive Tire

☐ Photo of Seat area

COMMENTS:

Figure 1. Vehicle information form.

5) Please fill in a *vehicle information form* for each vehicle/machine measurement (***Fig 1.***). This form contains most of the potential 'predictors of WBV exposure' that we need for model development.

6) Each time you start and stop the WBV logger, please take note of the start and stop time (clock time).

7) Vehicle type – ask or see the 'SK farm info' document in the 'Background Information' folder for a description of each type of machine.

8) The position of the load: If the load is carried behind the cab or pulled behind the vehicle, record 'behind'. If the load is pushed ahead of the vehicle or carried in front of the cab, record 'front'. If the load is right under the driver, record 'under.'

9) Pulling a load – describe whether or not a tractor/machine was always pulling something during the measurement. If the tractor sometimes pulled and sometimes didn't, record it as 'mixed'. Also, add a description of the load being pulled: bailer, grain trailer, seeder, water cart, etc.

10) Tire type – wheels are round like most vehicles, tracks are long belts or chains that have a lot of contact with the ground.

11) Tread type – For wheels only. Do not record for tracks. If unsure, make a comment and be sure to take a photo so we can discuss it.

12) Tire radius – HALF the diameter – from the centre of the axle to the edge of the wheel. Do not collect for track vehicles

    Please take a photo of the whole vehicle, wheel, and seat area. If you are unable to fill in the whole sheet in the field, this can help us decide later

13) If you are unsure about something, take some notes in the comments field, and we can discuss the categories at a team meeting

EQUIPMENT DESCRIPTION

1) *MWX8 DataLOG*
2) *Triaxial accelerometer (series 2A)*
3) *Rubberized seat pad*
4) *AA Lithium batteries (for high tech devices)*
5) *MicroSD card (2GB)*
6) *Mounting screws (accelerometer to seat pad)*
7) *Lenovo X1 Carbon laptop (device configuration)*
8) *MicroSD-to-USB adaptor (data transfer to laptop)*

OVERVIEW OF EQUIPMENT & CONNECTIONS

1. Connect the triaxial accelerometer to the DataLOG. X inserts into analogue input 1. Y inserts into analogue input 2. Z inserts into analogue input 3. Use the red dots to align the accelerometer connectors with inputs on the DataLOG (***Fig. 2***).

Figure 2. MWX8 DataLOG and series 2A triaxial accelerometer.

2. Insert batteries into the DataLOG (under analogue inputs 5−8).

3. Insert 2GB MicroSD card into the DataLOG (***Fig. 3***).

Figure 3. MicroSD card & DataLOG

4. Mount the triaxial accelerometer in the rubberized seat pad. The accelerometer cable will fit in the indentation of the seat pad when the accelerometer is aligned correctly (***Fig. 4***).

5. Fasten the accelerometer to the seat pad with a small screw through the top of the seat pad using a Phillips (cross-head) screwdriver (***Fig. 5***).

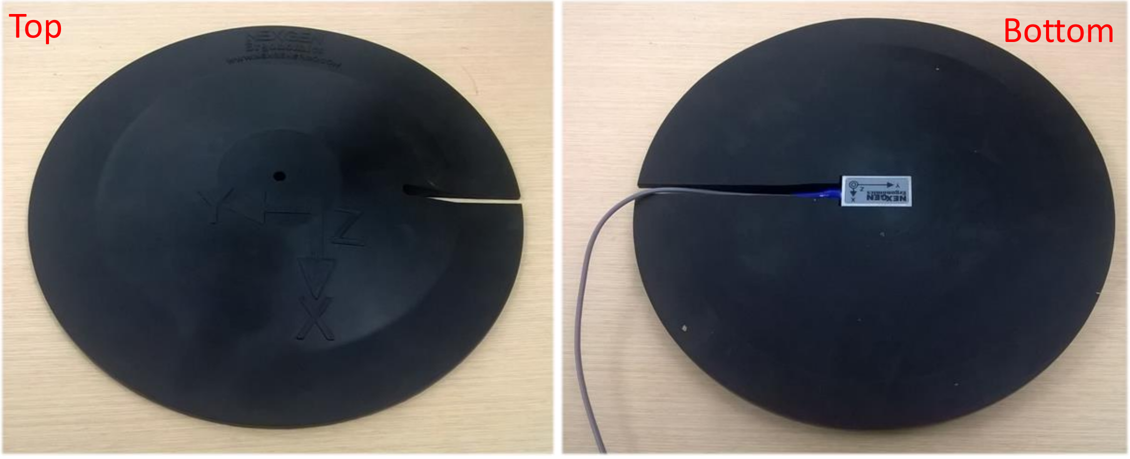


Figure 4. Series 2A triaxial accelerometer mounted in rubberized seat pad.

Figure 5. Mounting screw for the accelerometer through the top of the rubberized seat pad.

EQUIPMENT CONFIGURATION

MWX8 DataLOG

Configure each device before arriving onsite for data collection. Once each DataLOG is configured, the settings are saved to the DataLOG and will remain unchanged, even if the unit is powered down and the batteries are removed.

1) Power on the DataLOG (button directly below display)
2) Open Biometrics DataLOG software on the laptop (Lenovo XI Carbon)
3) Ensure the DataLOG is close to the laptop (Bluetooth communication)
4) In the software, scan for devices (Select “***Setup***” → “***Port***” → “***Bluetooth Scan”***)
5) Ensure the DataLOG units are detected (Select “***View***” → “***Detected Units***”)
6) Configure the accelerometers using settings in ***Fig. 6***
    a) Select “***Setup***” → “***Analogue Inputs***”

Series 2A Accelerometers

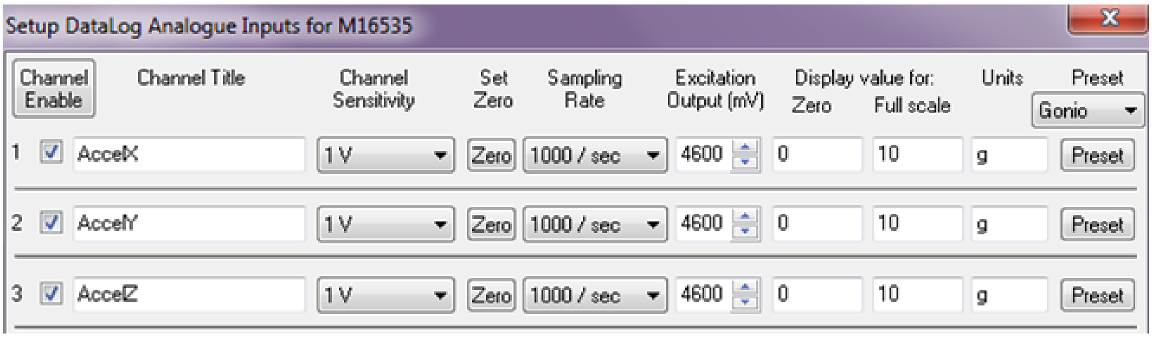
Accelerometers must be configured before arriving onsite for data collection. The accelerometers are currently set for data collection of 1000 Hz, and we will use this configuration for the entire study.

Each accelerometer channel (X, Y, & Z) has a hard-wired anti-aliasing filter, which must be adjusted depending on the desired sampling rate (***Fig. 7***).

1) Set the ***filter to 100 Hz*** for a ***sample rate of 200 Hz***

2) Set the ***filter to 500 Hz*** for a ***sample rate of 1000 Hz***

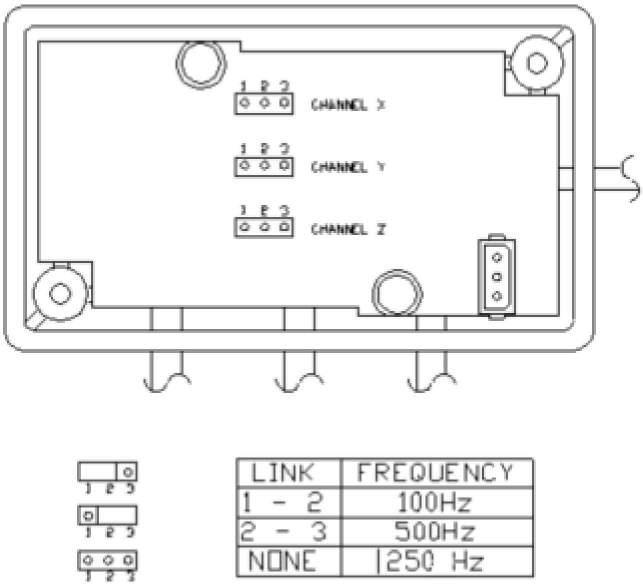
3) Set the ***filter to 1250 Hz*** for a ***sample rate of 2500 Hz***



Setup DataLog Analogue Inputs for M16535

	Channel Enable	Channel Title	Channel Sensitivity	Set Zero	Sampling Rate	Excitation Output (mV)	Display value for: Zero	Full scale	Units	Preset Gonio
1	☑	AccelX	1 V	Zero	1000 / sec	4600	0	10	g	Preset
2	☑	AccelY	1 V	Zero	1000 / sec	4600	0	10	g	Preset
3	☑	AccelZ	1 V	Zero	1000 / sec	4600	0	10	g	Preset

Figure 6. Configuration settings for triaxial accelerometers. Ensure the configuration settings match this display (channel sensitivity – 1V; sample rate – 1000 Hz; excitation output – 4600 mV; full-scale range – 10 g).



LINK	FREQUENCY
1 - 2	100Hz
2 - 3	500Hz
NONE	1250 Hz

Figure 7. For a sample rate of 200 Hz, set the wire links on pins 1 − 2 for all 3 channels (X, Y, & Z). For a sample rate of 1000 Hz, set the wire links on pins 2 – 3. For a sample rate of 2500 Hz, remove the wire links from the pins entirely.

DATA COLLECTION

1. Verify all the equipment components and supplies are present before leaving the lab for data collection, and store them in the pelican case and onsite pouch (***Fig. 8***).

Figure 8. Equipment for measuring WBV. Measurement equipment and supplies are to be stored and transported in a pelican case and onsite equipment bag.

Figure 9. Equipment stored in the onsite equipment bag.

Equipment stored in the pelican case:

1. Triaxial accelerometer w/ batteries and microSD card (2GB).

Also: tablet and I2M monitors

Equipment stored in the onsite equipment bag:

1. duct tape, carpet tape,
2. Phillips screwdriver,
3. scissors,
4. mounting screws (for the accelerometer to seat pad),
5. extra batteries,
6. rubberized seat pad with the triaxial accelerometer.

2. Setup the vibration equipment inside the vehicle or machinery.

- **a.** Before leaving the lab, mount the triaxial accelerometer to the rubberized seat pad, and screw the accelerometer to the seat pad, as previously described in ***Figures 4 & 5.*** Doing this ahead of time and storing the seat pad and accelerometer together in the onsite pouch will reduce our setup time.
- **b.** Before leaving the lab, apply strips of double-sided tape to the bottom side of the seat pad. Once you are ready to make a measurement on a farm, remove the non-stick layers of the double-sided tape strips, and secure the seat pad to the seat of the vehicle/machinery (***Fig. 10***). You may only need to use 2-3 strips of double-sided tape for each measurement.
- **c.** Ensure that the X-axis arrow on the seat pad is pointing towards the steering wheel (forward).
- **d.** Use duct tape to make a criss-cross pattern over the seat pad (***Fig. 10***).
- **e.** Place one strip of duct tape across the seat and over the accelerometer (to ensure it does not get caught by the equipment operator during operation).
- **f.** If you use scissors to cut the tape, **cut the tape far away** from the seat pad, accelerometer, and wires to avoid accidentally damaging the equipment.

3. Connect the triaxial accelerometer to the DataLOG, as in ***Fig. 2***.

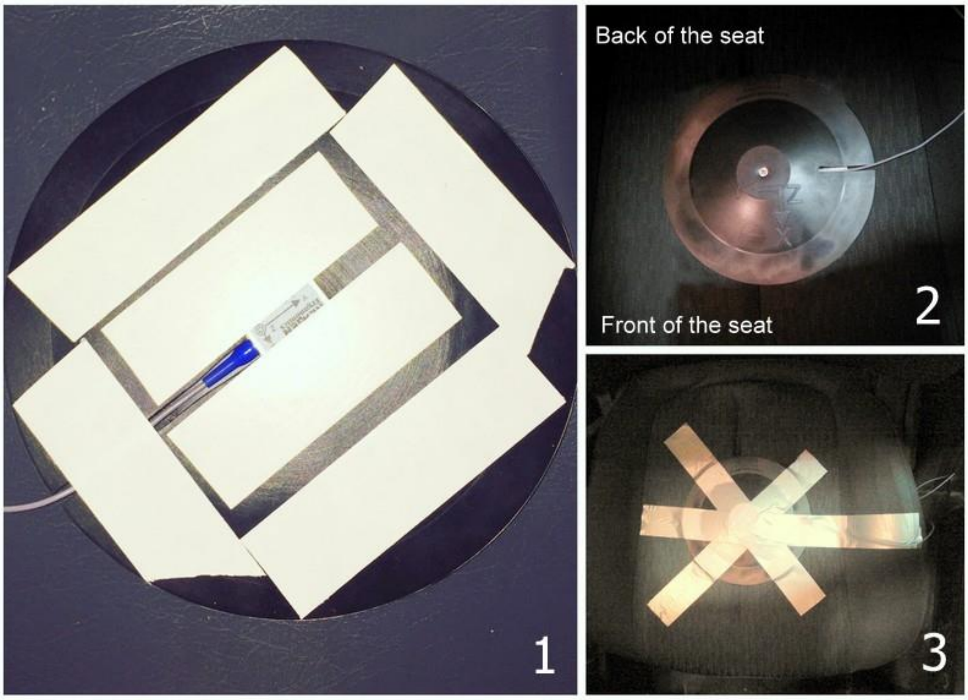


Figure 10. Secure the seat pad and accelerometer to the seat using carpet tape (steps 1−2). Use duct tape over the seat pad and accelerometer cable for further protection (step 3).

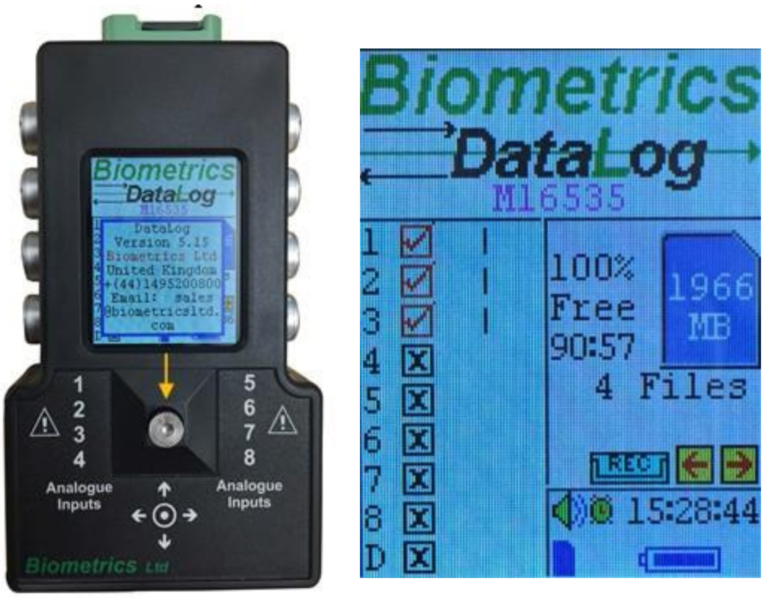


Figure 11. (Left) Press the joystick button (yellow arrow) to turn on the DataLog. (***Right***) The main screen will appear, which shows the analog channels (left side of the screen), available memory (top right of screen), and battery life (bottom right of screen).

4. Turn on DataLOG by pressing the joystick button once (***Fig. 11***). The main screen should appear after a few seconds (***Fig. 11***).

- **a.** Ensure that the DataLOG is receiving communication from the triaxial accelerometer (channel indicators on the left side of the screen).

b. Ensure there is sufficient battery power for the data collection (half battery for 4 h; a full battery for 8 h). Change the batteries if they are too low.

c. Ensure the MicroSD memory card is in the DataLOG, and there is sufficient storage space for the data collection (100 MB per hour).

5. Zero all channels using the joystick control (***Fig. 12***). Press the joystick button to bring up the options menu. Go to ***"Zero"***, select ***"All"***, and ***"Confirm"***.

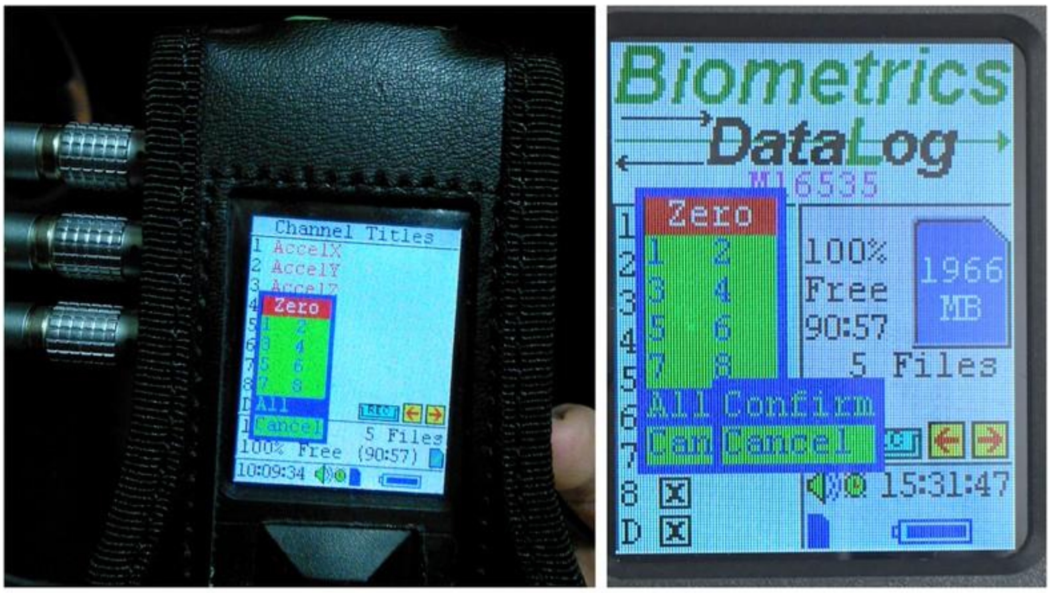


Figure 12. Zero all channels using the joystick control on the DataLOG.

6. Start recording data using the joystick control.

a. Ensure the data is being saved to MicroSD (***Fig. 13***). Press the joystick button to bring up the options menu. Go to ***"Record"***, select ***"Save To"***, and ***"Card Only"***.

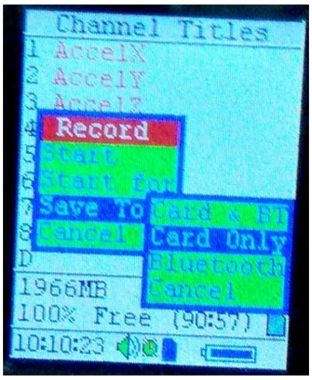


Figure 13. Save to "Card Only".

b. Start data collection (***Fig. 14***). Press the joystick button to bring up the options menu. Go to ***"Record"***, select ***"Start"***, and ***"Confirm"***.

Figure 14. Begin recording data.

7. Carefully ***store the dataLOG*** in the ***Pelican Case***. If there is not sufficient room for the case, use the ***Onsight Pouch***.

a. Ensure the wires are not compressed when closing the case (there is a small groove drilled out for the wires).

b. Secure the pelican case with the DataLOG in the cab of the vehicle, and ensure the case is not obtrusive to the driver (stored beside, below, or behind the seat).

c. Ensure that the case cannot move during vehicle operation (***Fig. 15***).

8. If the wire from the accelerometer may become caught on the worker, fix the wire to the vehicle using duct tape.

9. It is good practice to tape the cable in "s-loop" near the case or pouch, so that if the worker accidently catches the wire, there is slack in the cable to minimize damage.

Figure 15. Place the DataLOG in the Pelican Case (or if there is insufficient space, the Onsight Pouch), and secure the case inside the vehicle cab.

10. Once the worker has completed their driving task, stop recording data, and shut down the DataLOG.

   a. To stop recording data, bring up the options menu by pressing the joystick button, go to ***"Record"***, select ***"Stop"***, and ***"Confirm"***.

   b. To shutdown DataLOG, press the joystick button, go to ***"Shutdown"***, and ***"Confirm"***.

11. At the end of the day, download the data on Jade drive. If you are away again overnight, download the data on the Lenovo Carbon X1 Laptop and back it up to Data share once you get back to the lab. Please follow the data storage and naming convention (outlined later in the document).

DATA STORAGE

File Storage

We need to ensure that ***all data*** are ***downloaded*** using the established file directory, ***labelled*** using the standard convention, so the files are linked to correct person, and ***backed up*** in the event of a computer failure.

- A ***unique identifier*** will be assigned ***to each person*** at the beginning of the day.
- The ***daily questionnaire*** will serve as the ***master file*** that links the participant's name with a unique participant ID.
- A ***primary contact*** with a farmer will have an ***ID code of '1'***. A ***secondary contact*** with another person on the farm will have an ***ID code starting with '2'***.
- ***Label the WBV data using this participant ID***. Under no circumstances should the participant's name be used as an identifier for measurement of WBV.

1. At the end of the day, download all ***WBV files*** to the ***Lenovo XI Carbon Laptop*** and ***External Hard Drive***

   a. Eject the MicroSD card from the DataLOG, and insert it into the MicroSD-to-USB adapter

   b. Mount the adapter to the laptop, and copy & paste the data files (.rwx) from the day to Lenovo Carbon X1 Laptop.

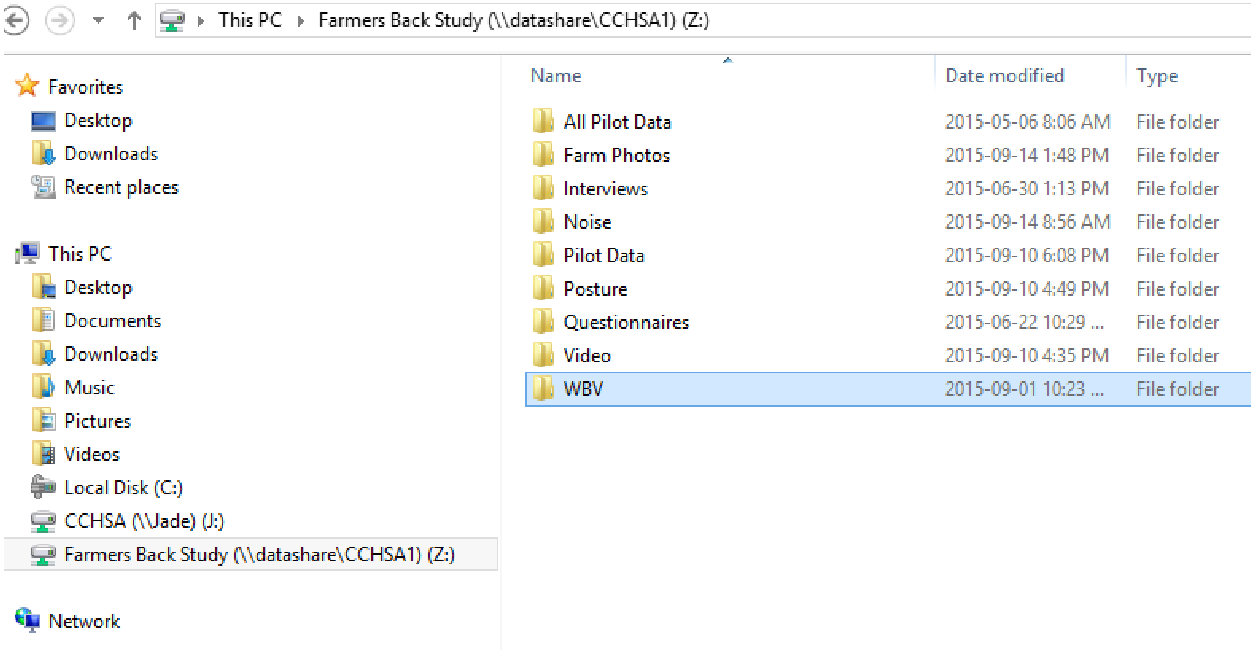
   c. Next, connect the external hard drive to the laptop (USB cable)

   d. Copy & paste the files from the Lenovo Carbon X1 Laptop to the external hard drive ***Farmers Back Study (\\datashare\CCHSA1)(Z:).***

   e. Safely eject the MicroSD-to-USB adaptor and the external hard drive from the laptop, and re-insert the MicroSD card into the DataLOG.

2. Upon returning to the lab, copy and paste files from the Lenovo Carbon X1 Laptop onto ***Farmers Back Study (\\datashare\CCHSA1)(Z:)*** (password protected permanent data storage)

a. The laptop is already mapped onto Jade, which can be accessed on the network at the CCHSA (***Fig. 16***)



Name	Date modified	Type
All Pilot Data	2015-05-06 8:06 AM	File folder
Farm Photos	2015-09-14 1:48 PM	File folder
Interviews	2015-06-30 1:13 PM	File folder
Noise	2015-09-14 8:56 AM	File folder
Pilot Data	2015-09-10 6:08 PM	File folder
Posture	2015-09-10 4:49 PM	File folder
Questionnaires	2015-06-22 10:29 ...	File folder
Video	2015-09-10 4:35 PM	File folder
WBV	2015-09-01 10:23 ...	File folder

b. Copy and paste the files to ***Farmers Back Study (\\datashare\CCHSA1)(Z:)*.**

Figure 16. Copy and paste file onto datashare.

3. Once the data is backed up on ***Farmers Back Study (\\datashare\CCHSA1)(Z:)***, it will be cleared the micro-SD.

Naming Convention

1. Each file name is coded with the following information:
    - Farmer ID (6 digits, 4-2)
    - Date of measurement (6 digits)
    - Visit 1, 2, or 3 (1 digit)
    - Type of measurement (3 letters)
    - Vehicle type & number
    - Measurement number (1 letter)

2. An example for WBV:
    - FarmerID_YYMMDD_Visit#_WBV_VehicleType &#_Measurement#
    - 1001-01_150204_1_WBV_Tractor02_a

- We may measure several vehicles each day, and even several of the same vehicle type.
    - List the first tractor as ‘tractor 01’, second tractor ‘tractor02’, etc …
    - List the first skid steer is ‘skid steer01’, then ‘skid steer02’, etc …
- For multiple measurements on the same vehicle (e.g. on ‘tractor02’), use a lowercase letter (‘a’, ‘b’, ‘c’, etc.)
- Stored separate files for each vehicle whenever possible.

DATA ANALYSIS

This is performed back at the lab, after the measurement day. It may be completed well after data collection occurs.

Biometrics Software

1. Use the MicroSD-to-USB adaptor to open the data files on the card using the Lenovo PC (in the Ergonomics Laboratory)
2. Open the Biometrics software (icon on desktop)
3. Import the data file (.rwx extension)
    - **a.** Select “***File***” → “***Import***” → “***Open File***” → “***Biometrics (E:)***”
    - **b.** Open file (.rwx)
4. Ensure that “***AccelX***”, “***AccelY***”, “***AccelZ***” are selected under “***Trace***” in the top left corner of the software ***(Fig. 17)***
5. Save the file with a .log extension for analysis in VATS

a. Select “***File***” → “***Save***” (.log)

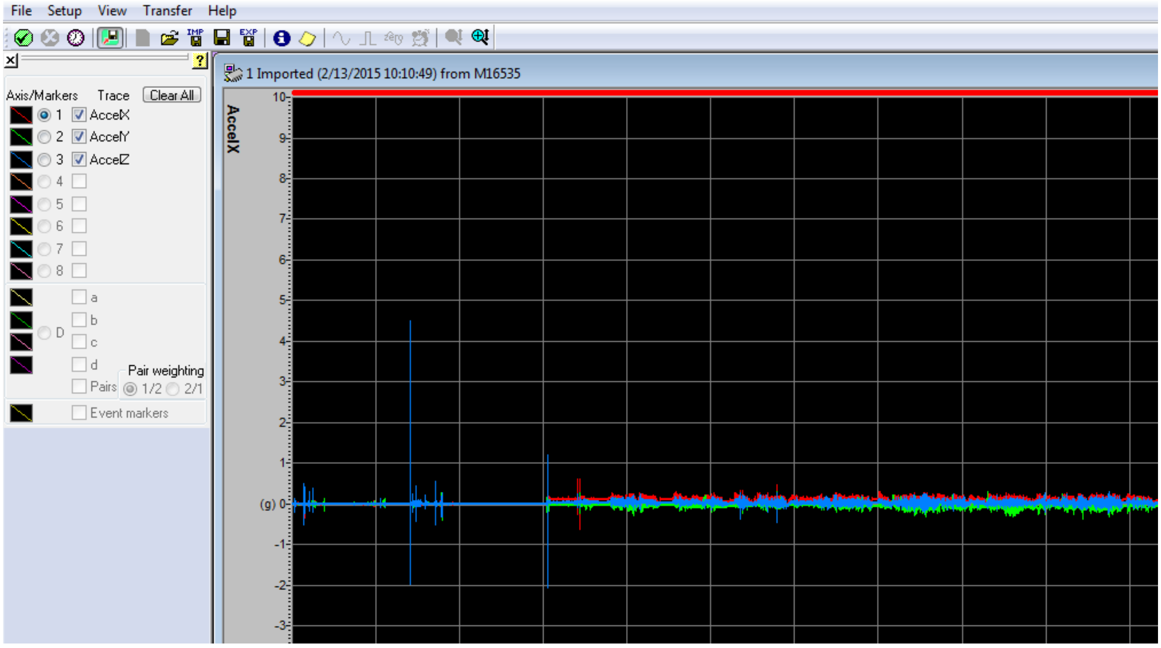


Figure 17. Import the data from the MicroSD card into the Biometrics Software.

VATS Software

1. Open the .log file in VATS (previously saved using Biometrics)

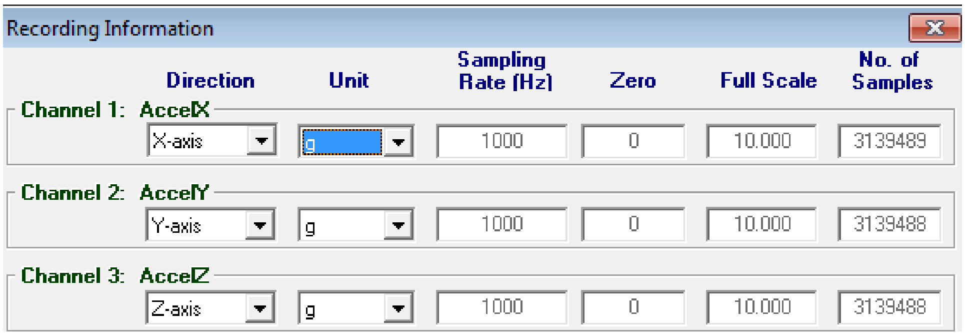
   a. Select “***File***” → “***Open***” (.log)

2. Specify the data on each channel (***Fig. 18***)

   a. Channel 1: AccelX → “***x-axis***” (fore-aft)

   b. Channel 2: AccelY → “***y-axis***” (side-side)

   c. Channel 3: AccelZ → “***z-axis***” (up-down)



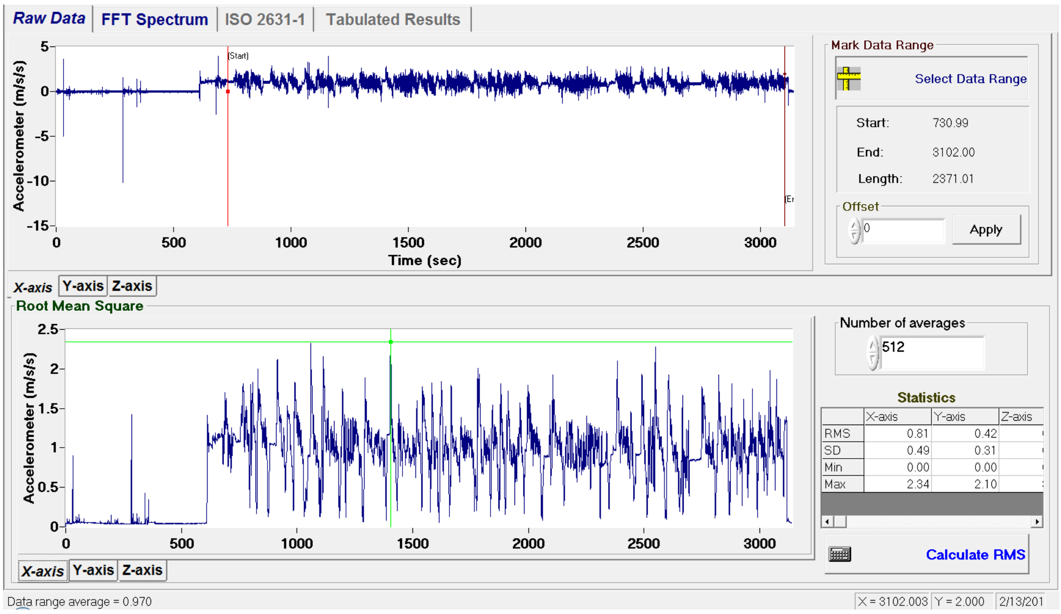
Recording Information

	Direction	Unit	Sampling Rate [Hz]	Zero	Full Scale	No. of Samples
Channel 1: AccelX	X-axis	g	1000	0	10.000	3139489
Channel 2: AccelY	Y-axis	g	1000	0	10.000	3139488
Channel 3: AccelZ	Z-axis	g	1000	0	10.000	3139488

Figure 18. Specify the data collected on each channel, and select units of g’s. Ensure the correct sampling rate (1000 Hz) and full-scale range (10 g).

3. Select “***Whole Body***” → “***ISO 2631-1***”

4. On the ***raw data tab***, select the ***data range*** of interest using ***red whiskers*** (***Fig. 19***)



Mark Data Range

Start: 730.99

End: 3102.00

Length: 2371.01

Offset: 0

Number of averages: 512

Statistics

	X-axis	Y-axis	Z-axis
RMS	0.81	0.42	
SD	0.49	0.31	
Min	0.00	0.00	
Max	2.34	2.10	

Data range average = 0.970

X = 3102.003 Y = 2.000 2/13/201

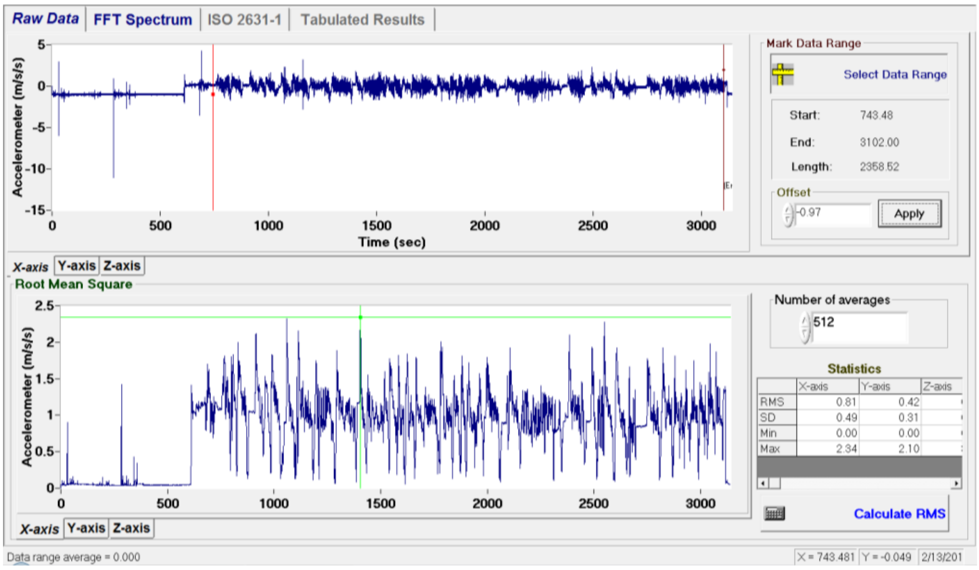
Figure 19. Use the red whiskers to select the appropriate data range.

5. Apply “***offsets***” for “***X***”, “***Y***”, & “***Z***” axes (***Fig. 19***)

   a. Manually enter the offset for each channel to de-bias the signal (top right of the software)

   b. Ensure ***mean data range equals 0*** for the “***X***”, “***Y***”, & “***Z***” axes (bottom left of the software)

6. ***“Calculate RMS”*** acceleration (button on bottom right of the software)



Mark Data Range

Start: 743.48

End: 3102.00

Length: 2358.52

Offset: -0.97

Number of averages: 512

Statistics

	X-axis	Y-axis	Z-axis
RMS	0.81	0.42	
SD	0.49	0.31	
Min	0.00	0.00	
Max	2.34	2.10	

Data range average = 0.000

X = 743.481 Y = -0.049 2/13/201

Figure 20. Apply offsets to debias the signal, so that the data range average for each axis is equal to 0. Calculate root-mean-squared acceleration.

7. On the ***FFT Spectrum Tab***, select the ***Filtering*** and ***FFT specifications*** (***Fig. 21***)

   a. ***Butterworth Filter*** → Order – 2; low cutoff– 0.1 Hz; high cutoff– 500 Hz.

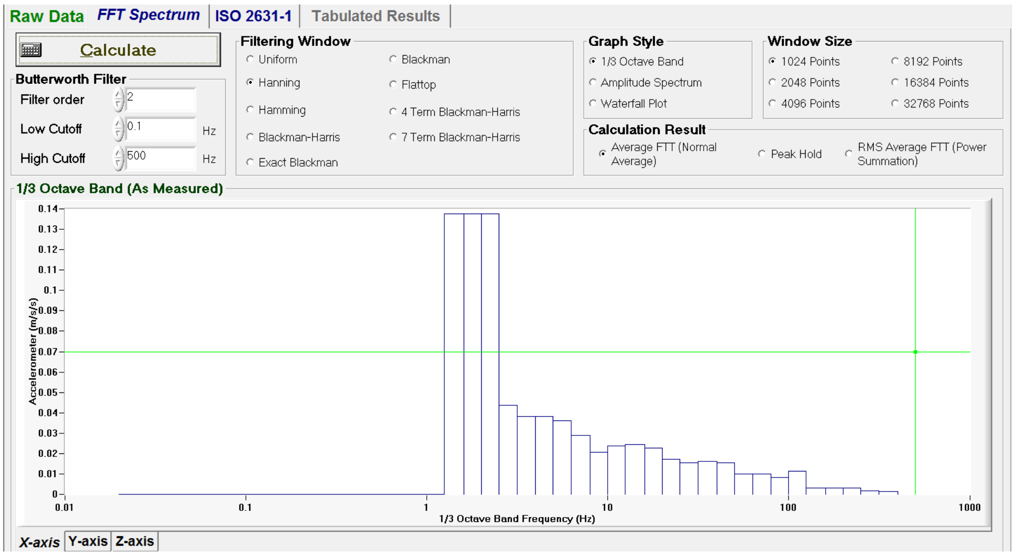
   b. ***Filtering Window*** → Hanning

   c. ***Graph Style*** → 1/3 octave band

   d. ***Window Size*** → 1024 points

   e. ***Calculation Result*** → Average FFT

8. ***"Calculate"*** FFT spectrum using the button on top left of the software (***Fig. 21***)



Butterworth Filter
Filter order 2
Low Cutoff 0.1 Hz
High Cutoff 500 Hz

Filtering Window
○ Uniform
● Hanning
○ Hamming
○ Blackman-Harris
○ Exact Blackman
○ Blackman
○ Flattop
○ 4 Term Blackman-Harris
○ 7 Term Blackman-Harris

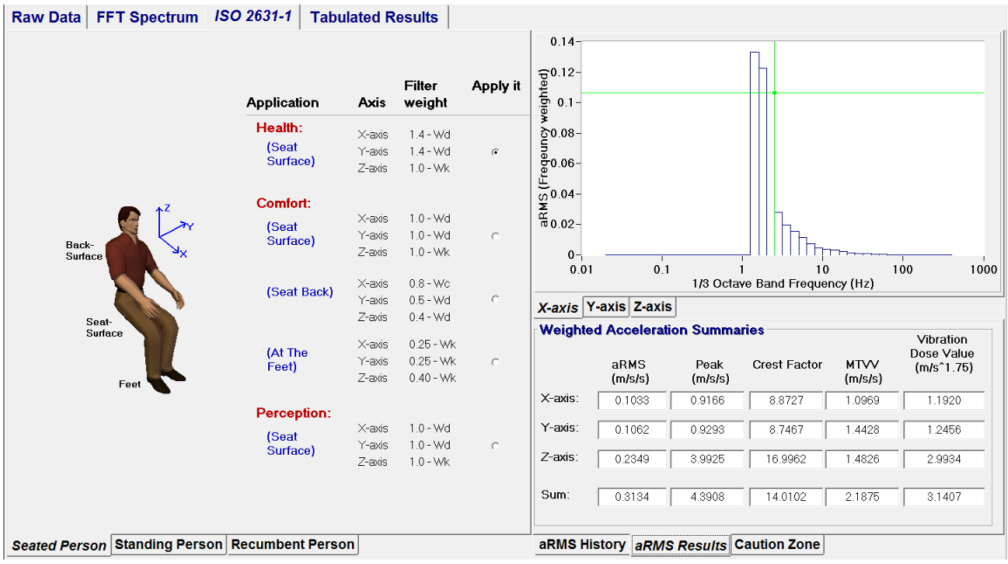
Graph Style
● 1/3 Octave Band
○ Amplitude Spectrum
○ Waterfall Plot

Window Size
● 1024 Points
○ 2048 Points
○ 4096 Points
○ 8192 Points
○ 16384 Points
○ 32768 Points

Calculation Result
● Average FFT (Normal Average)
○ Peak Hold
○ RMS Average FFT (Power Summation)

Figure 21. Select filtering and FFT specifications. Calculate the FFT spectrum.

9. On the ***ISO 2631-1 Tab*** select **"*Health: Seated Surface*"** to apply the correct weighting factors (***Fig. 22***)



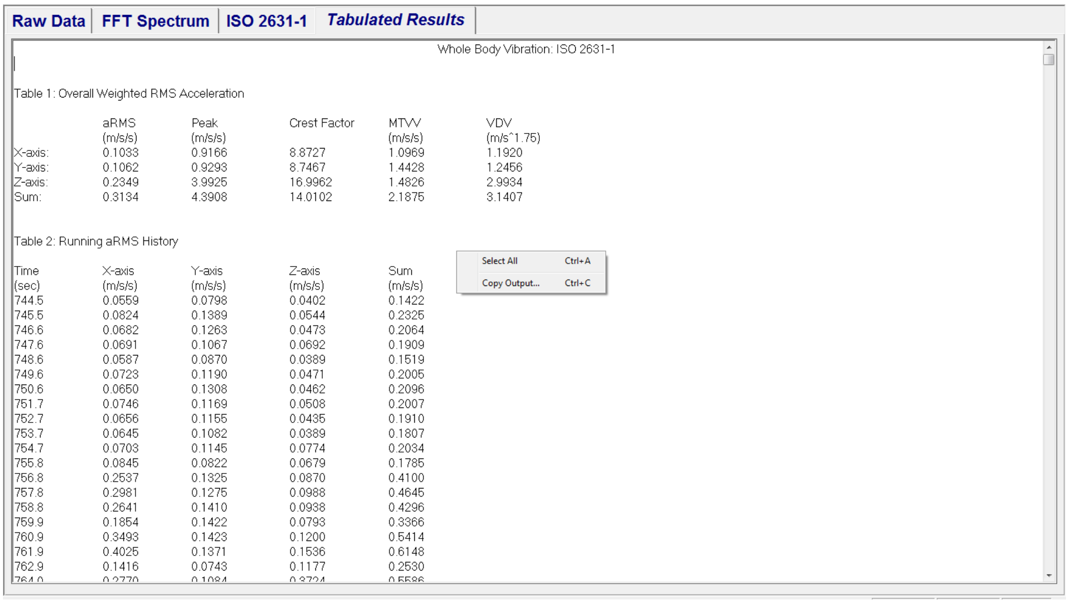
Application	Axis	Filter weight	Apply it
Health: (Seat Surface)	X-axis Y-axis Z-axis	1.4 - Wd 1.4 - Wd 1.0 - Wk	●
Comfort: (Seat Surface)	X-axis Y-axis Z-axis	1.0 - Wd 1.0 - Wd 1.0 - Wk	○
(Seat Back)	X-axis Y-axis Z-axis	0.8 - Wc 0.5 - Wd 0.4 - Wd	○
(At The Feet)	X-axis Y-axis Z-axis	0.25 - Wk 0.25 - Wk 0.40 - Wk	○
Perception: (Seat Surface)	X-axis Y-axis Z-axis	1.0 - Wd 1.0 - Wd 1.0 - Wk	○

Weighted Acceleration Summaries

	aRMS (m/s/s)	Peak (m/s/s)	Crest Factor	MTVV (m/s/s)	Vibration Dose Value (m/s^1.75)
X-axis:	0.1033	0.9166	8.8727	1.0969	1.1920
Y-axis:	0.1062	0.9293	8.7467	1.4428	1.2456
Z-axis:	0.2349	3.9925	16.9962	1.4826	2.9934
Sum:	0.3134	4.3908	14.0102	2.1875	3.1407

Figure 22. Select health for a seated surface to apply the suitable weighting factors.

10. View a summary of results on the ***Tabulated Results Tab*** (***Fig. 23***)



```
                                                    Whole Body Vibration: ISO 2631-1

Table 1: Overall Weighted RMS Acceleration

          aRMS      Peak      Crest Factor  MTVV      VDV
          (m/s/s)   (m/s/s)                 (m/s/s)   (m/s^1.75)
X-axis:   0.1033    0.9166    8.8727        1.0969    1.1920
Y-axis:   0.1062    0.9293    8.7467        1.4428    1.2456
Z-axis:   0.2349    3.9925    16.9962       1.4826    2.9934
Sum:      0.3134    4.3908    14.0102       2.1875    3.1407


Table 2: Running aRMS History

Time      X-axis    Y-axis    Z-axis        Sum
(sec)     (m/s/s)   (m/s/s)   (m/s/s)       (m/s/s)
744.5     0.0559    0.0798    0.0402        0.1422
745.5     0.0824    0.1389    0.0544        0.2325
746.6     0.0682    0.1263    0.0473        0.2064
747.6     0.0691    0.1067    0.0692        0.1909
748.6     0.0587    0.0870    0.0389        0.1519
749.6     0.0723    0.1190    0.0471        0.2005
750.6     0.0650    0.1308    0.0462        0.2096
751.7     0.0746    0.1169    0.0508        0.2007
752.7     0.0656    0.1155    0.0435        0.1910
753.7     0.0645    0.1082    0.0389        0.1807
754.7     0.0703    0.1145    0.0774        0.2034
755.8     0.0845    0.0822    0.0679        0.1785
756.8     0.2537    0.1325    0.0870        0.4100
757.8     0.2981    0.1275    0.0988        0.4645
758.8     0.2641    0.1410    0.0938        0.4296
759.9     0.1854    0.1422    0.0793        0.3366
760.9     0.3493    0.1423    0.1200        0.5414
761.9     0.4025    0.1371    0.1536        0.6148
762.9     0.1416    0.0743    0.1177        0.2530
```

a. Right click on the results summary, "***Select All***"

b. Right click again, and "***Copy Output***"

c. ***Paste*** the ***output*** in an ***MS Excel*** file and ***save*** results (.xlsx extension)

Figure 23. Copy the data from the tabulated results tab and paste into MS Excel.

APPENDIX B: Vehicle Information Form

Saskatchewan Farmers Back Study

<table>
<tr><td>Date (year, month, day)|___|___|___|___| |___|___| |___|___|</td><td>Subject ID |___|___|___|___|-|___|___|</td><td>Vehicle #
|___|___|</td></tr>
<tr><td colspan="3">Researcher initials: □ MIK □ XZ □ AK □ CT</td></tr>
</table>

<table>
<tr><td>Ride 1</td><td>Measurement start time: |___|___|:|___|___|</td><td>Measurement End time: |___|___|:|___|___|</td></tr>
<tr><td>Ride 2</td><td>Measurement start time: |___|___|:|___|___|</td><td>Measurement End time: |___|___|:|___|___|</td></tr>
<tr><td>Ride 3</td><td>Measurement start time: |___|___|:|___|___|</td><td>Measurement End time: |___|___|:|___|___|</td></tr>
<tr><td><i>As they start up the vehicle, ask if it works</i></td><td>Operation hours:
|___|___|___|___|___|___|___|___|</td><td>Odometer:
|___|___|___|___|___|___|___|___|</td></tr>
</table>

<table>
<tr><td><i>Inside the cab:</i></td><td>Seat suspension
☐ Rigid ☐ Air/Pneumatic/hydraulic
☐ Spring ☐ Other</td><td>Arm Rest
☐ Yes
☐ No</td><td>Seat Cushion
☐ Yes
☐ No</td><td>Back Rest
☐ Yes
☐ No</td><td>Additional Cushion
☐ Yes
☐ No</td></tr>
</table>

<table>
<tr><td>Vehicle Type
☐ Tractor ☐ seeder ☐ pick-up
☐ Combine ☐ skid steer ☐ other:</td><td>Number of axels (not including trailers):
|___|___|</td></tr>
<tr><td>Describe (colour, size, etc.)</td><td>Make and model:</td></tr>
</table>

<table>
<tr><td>Is the LOAD:
☐ in front of the cab
☐ behind the cab
☐ under the cab</td><td>Pulling a load
☐ Always
☐ Mixed
☐ Never</td><td>Load Type
(i.e. seeder, trailer)</td><td>Tire type
☐ Wheel
☐ Track</td><td>Dual tires?
☐ Yes
☐ No</td><td>Drive
☐ 2WD
☐ FWA/AWD
☐ 4WD</td><td>Tread type
☐ Slick
☐ Heavy</td><td>Tire Radius (cm)
|___|___|___|</td></tr>
</table>

Did you get: ☐ Photo of Vehicle ☐ Photo of Drive Tire ☐ Photo of Seat area	**COMMENTS:**

The following items are to be asked at the end of the day during the daily questionnaire.

Date (year, month, day)**|___|___|___|___| |___|___| |___|___|**

Subject ID |___|___|___|___|-|___|___|

Vehicle # |___|___|

Please estimate the total time you spent on this machine today (while it was running): |___|___|:|___|___|
H H M M

Power steering
☐ **Yes**
☐ **No**

Transmission
☐ **Manual**
☐ **Automatic**
☐ **Other**

 # Gears
|___|___|

Gross Vehicle weight (kg)
|___|,___|___|___|,|___|___|___|

Horsepower rating:
|___|___|___|___|___|

Any Additional comments:

If needed, the following may be used to track additional rides on the same vehicle:

<table>
<tr><td>Ride 4</td><td>Measurement start time: |___|___|:|___|___|</td><td>Measurement End time: |___|___|:|___|___|</td></tr>
<tr><td>Ride 5</td><td>Measurement start time: |___|___|:|___|___|</td><td>Measurement End time: |___|___|:|___|___|</td></tr>
<tr><td>Ride 6</td><td>Measurement start time: |___|___|:|___|___|</td><td>Measurement End time: |___|___|:|___|___|</td></tr>
<tr><td>Ride 7</td><td>Measurement start time: |___|___|:|___|___|</td><td>Measurement End time: |___|___|:|___|___|</td></tr>
<tr><td>Ride 8</td><td>Measurement start time: |___|___|:|___|___|</td><td>Measurement End time: |___|___|:|___|___|</td></tr>
<tr><td>Ride 9</td><td>Measurement start time: |___|___|:|___|___|</td><td>Measurement End time: |___|___|:|___|___|</td></tr>
</table>

APPENDIX C: Daily Exposure Questionnaire

Saskatchewan
Farmers
Back
Study

Daily Questionnaire

Worker ID
(interviewer to fill in) |__|__|__|__|-|__|__|
Visit Number
☐1 ☐2 ☐3 ☐4 |__|__|/|__||__|/|__|__|__|__|
D D / M M / Y Y Y Y

Researcher initials: ☐ MIK ☐ XZ ☐ AK ☐ CT

This questionnaire should be filled out after posture and vibration measurements.

If you have not completed your entire workday, consider the portion of your workday when the measurements were made.

We are interested in the type of work you did ***today*** on your farm. Please answer the following questions to the best of your ability. Feel free to ask if something seems unclear.

1) Did you use any vehicles or machinery today? Yes ^{1}☐ No ^{2}☐

   a) IF YES For each of these vehicles/machinery, how often did you sit in these postures? '*Often*' means more than half the time, '*Occasionally*' means less than half the time

EQUIPMENT	**Bent forward**	**Twisted**	**Leaning on backrest**
Tractor	_often _ occasionally _never	_often _ occasionally _never	_often _ occasionally _never
Combine	_often _ occasionally _never	_often _ occasionally _never	_often _ occasionally _never
Sprayer	_often _ occasionally _never	_often _ occasionally _never	_often _ occasionally _never
Air seeder	_often _ occasionally	_often _ occasionally	_often _ occasionally

	_never	_never	_never
All-terrain vehicle	_often _ occasionally _never	_often _ occasionally _never	_often _ occasionally _never
Other 1	_often _ occasionally _never	_often _ occasionally _never	_often _ occasionally _never
Other 2	_often _ occasionally _never	_often _ occasionally _never	_often _ occasionally _never
Other 3	_often _ occasionally _never	_often _ occasionally _never	_often _ occasionally _never

2) Of the time you operated vehicles/machinery today, what proportion of the time was spent idling? ____%

3) Overall, what level of vibration, jolts, or jostling would you say you were exposed to today? (select a number from 0-10)

No vibration — Unable to stay on seat

0 1 2 3 4 5 6 7 8 9 10

4) How often does your vehicle/machinery jerk or jolt so much that you are lifted up out of your seat?
   a) _ Never
   b) _ Less than 5 times a day
   c) _ More than 5 times a day, but less than 5 times an hour
   d) _ More than 5 times an hour, but less than 5 times a minute
   e) _ More than 5 times a minute

5) How often did your seat ‘bottom out’ while you are driving?
   a) _ Never
   b) _ Less than 5 times a day
   c) _ More than 5 times a day, but less than 5 times an hour
   d) _ More than 5 times an hour, but less than 5 times a minute
   e) _ More than 5 times a minute

6) Did you experience discomfort while operating your vehicle or machinery?
   a) Yes ^{1}☐
   b) No ^{2}☐

   If yes, would you attribute this discomfort to any of the following:
   c) Sitting position
      i) Yes ^{1}☐
      ii) No ^{2}☐
   d) Heavy jolts

    i) Yes ^{1}☐
    ii) No ^{2}☐
e) Vertical (up/down) vibration
    i) Yes ^{1}☐
    ii) No ^{2}☐
f) Forward/ backward vibration
    i) Yes ^{1}☐
    ii) No ^{2}☐
g) Side-to-side vibration
    i) Yes ^{1}☐
    ii) No ^{2}☐

This page should be answered <u>only</u> if you operated a **vehicle or machinery today.**

7) What type of surfaces did you drive on today? What percentage of ***driving time*** did you spend on each?

Over smooth pavement or cement

___%

Gravel

___%

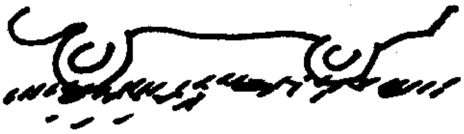
Packed earth

___%

Broken, cracked, or buckled dry earth

___%

Soft earth



___%

Rough Off-road (logs, rocks, ditches)

___%

Please note the total should equal 100%

How would you describe the hilliness
or grade you drove on today?

IF you were driving on a **field**…

What was planted in this field ***last*** year?
What was planted ***this*** year?
What is the row spacing?

8) While working today, how many minutes/<u>hours</u> did you do the following

Stand

___|___:___|___
H H : M M

Walk

___|___:___|___
H H : M M

Sitting

___|___:___|___
H H : M M

Crouching

___|___:___|___
H H : M M

Bend sideways

___|___:___|___
H H : M M

Back extended

___|___:___|___
H H : M M

Back bent >45

___|___:___|___
H H : M M

Back bent >90

___|___:___|___
H H : M M

Back Twisting

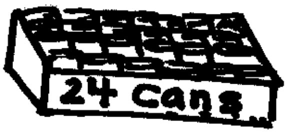
___|___:___|___
H H : M M

While working today, how long did you perform these tasks?

Perform any kind of manual handling: Lift, lower, carry, push or pull

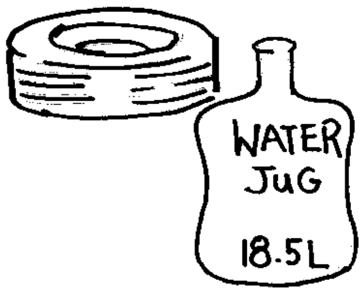
___|___:___|___
H H : M M

Handles loads 10-20lbs



___|___:___|___
H H : M M

Handle loads >20lbs



___|___:___|___
H H : M M

Handle loads far from your body (more than 20 inches)

___|___:___|___
H H : M M

APPENDIX D: Examples of agricultural machines measured in this study

1. Tractor (pulling a seeder behind)

2. Combine

3. Grain Truck

4. Pick-up truck

5. Sprayer

6. Swather

7. All-terrain vehicle (ATV)

8. Skid-steer

APPENDIX E: Model Selection Process

Table 7. Manual stepwise model selection for both lnRMS and lnVDV models with farmer and farm as random effects.

lnRMS Models	**Fixed effects number**	**Fixed effects variables**	**Variable with highest *P-value***
M0	8	vehicle year, seat suspension, tire size, transmission type, gears, horsepower, farm commodity, farm size	Gears *P-value*=0.9613
M1	7	vehicle year, seat suspension, tire size, transmission type, horsepower, farm commodity, farm size	Seat suspension: air *P-value*=0.8793
M2	6	vehicle year, tire size, transmission type, horsepower, farm commodity, farm size	Vehicle year *P-value*=0.6418
M3	5	tire size, transmission type, horsepower, farm commodity, farm size	Tire size *P-value*=0.6302
M4	4	transmission type, horsepower, farm commodity, farm size	Farm size *P-value*=0.2727
M5	3	transmission type, horsepower, farm commodity	Farm commodity: mixed *P-value*=0.1762
M6	2	transmission type, horsepower	All *P-value* less than 0.05
lnVDV Models	**Fixed effects number**	**Fixed effects variables**	**Variable with highest *P-value***
M0*	8	seat suspension, pulling a load, tread type, horsepower, jerk/jolt frequency, bottom-out frequency, farm commodity, farm size	Farm commodity: mixed *P-value*=0.9697
M1*	7	seat suspension, pulling a load, tread type, horsepower, jerk/jolt frequency, bottom-out frequency, farm size	Seat suspension: spring *P-value*=0.8793
M2*	6	pulling a load, tread type, horsepower, jerk/jolt frequency, bottom-out frequency, farm size	Tread type *P-value*=0.7343
M3*	5	pulling a load, horsepower, jerk/jolt frequency, bottom-out frequency, farm size	Jerk/jolt frequency *P-value*=0.4225
M4*	4	pulling a load, horsepower, bottom-out frequency, farm size	Horsepower *P-value*=0.2966
M5*	3	pulling a load, bottom-out frequency, farm size	Pulling a load *P-value*=0.3463
M6*	2	bottom-out frequency, farm size	Farm size *P-value*=0.1453
M7*	1	bottom-out frequency	All *P-value* less than 0.05

Note: M—model; RMS—frequency-weighted root-mean-squared acceleration; VDV—Vibration dose value. Ln: Log-transformed.

Table 8. Model performances.

Dependent variable: LnRMS	M0	M1	M2	M3	M4	M5	M6
AIC	78.6	84.3	79.6	76.0	73.4	71.3	71.9
BIC	81.8	87.4	82.7	79.1	76.5	74.4	75.1
R correlation	0.680	0.659	0.659	0.657	0.666	0.656	0.609
R square	46.24%	43.49%	43.41%	43.12%	44.34%	42.98%	37.14%
Dependent variable: LnVDV	M0*	M1*	M2*	M3*	M4*	M5*	M6*
AIC	125.6	124.7	121.6	119.0	115.9	102.9	100.5
BIC	128.7	127.8	124.7	122.1	116.2	103.2	103.6
R correlation	0.446	0.424	0.424	0.418	0.403	0.395	0.372
R square	19.91%	18.00%	17.95%	17.44%	16.22%	15.62%	13.86%

Note: M—model; RMS—frequency-weighted root-mean-squared acceleration; VDV—Vibration dose value; Ln: Log-transformed; R: correlation between actual measures and model predictions; AIC: the Akaike Information Criterion; BIC: the Bayesian Information Criterion.

APPENDIX F: Musculoskeletal Symptoms Prevalence among Farmers from the Saskatchewan Farmers Back Study.

Table 9. Prevalence of musculoskeletal symptoms among farmers in the Saskatchewan Farmers Back Study.

Body area	Point prevalence during the study period (n=31)	1-week prevalence (n=27)	Lifetime prevalence (n=29)
Head & Neck symptoms	16.12%		
Thoracic spine symptoms	16.12%		
Lower back symptoms	**54.84%**		
Low back pain		**40.74%**	**86.21%**
Arms symptoms	38.71%		
Hip & Thigh symptoms	25.81%		
Knee symptoms	22.58%		
Lower limb symptoms	19.35%		
Abdominal & Other symptoms	6.45%		

Note: n: the total number of farmers used for calculation.