# Ergonomics Evaluation of Exoskeletons in Agriculture

# Report to Alberta OHS Futures

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**Research Team**

This project was completed through the efforts of several investigators:

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**Stakeholder Advisory Group**

In addition to the investigator team, this study benefitted from the contributions of several stakeholders who provided insight into the agriculture industry and helped facilitate many aspects of the study. More details on the work of the Stakeholder Advisory Group is found in the methods section.

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**Photo Credits**

We are thankful to William Dekay for permitting use of his photographs in this report.

## Summary

BACKGROUND

Low back pain is a leading cause of years lived with disability in Canada. Among the agricultural workforce on the Canadian Prairies, there is a high prevalence of low back pain, adversely affecting quality of life and work ability. Prolonged back bending, a risk factor contributing to low back pain, is typical of many tasks in agriculture. However, changing the work environment may not be practical for labour-intensive stooped agricultural work tasks that occur at ground level, such as calving and repairing fences. Recent technological advancement offers supportive equipment that could mitigate adverse effects of prolonged back bending and heavy lifting in agriculture. An exoskeleton is a wearable structure that allows the back to be supported while bending forward and could be a solution to minimize spinal loads during back bending. Since it can reduce exposure to a number of risk factors, exoskeleton technology can potentially be an appropriate prevention strategy for back pain among farmers.

OBJECTIVES

This study investigated both directly-measured exposure to risk factors and farmer-reported usability experience of a commercially-available exoskeleton during work tasks in the agricultural sector. The specific goals were to:

1) better understand how the exoskeleton may assist farmers during work tasks and potentially reduce back pain and related disability
2) understand potential facilitators for, and barriers to, farmers' adoption of exoskeletons
3) support future improvements of exoskeleton technology to properly adapt to farming tasks and improve the health, quality of life, and productivity of farmers

METHODS

This study was conducted with the participation of a stakeholder advisory group which contributed insights and direction on the study methodology, interpretation of results, and knowledge translation plan. The study design was cross-sectional and mixed methods; that is, it combined both quantitative measures of exposure to hazards and qualitative assessment of farmer experience.

After selecting an appropriate exoskeleton and identifying farm tasks suitable for intervention, 15 farmers from 12 farms were visited and participated in their regular farm work on their farm both with and without the exoskeleton. They also participated in 3 standardized tasks, symmetric lifting, asymmetric lifting, and sustained bending, all with and without the exoskeleton. Standardized tasks were designed to include awkward trunk positions and manual handling demands that make up farm tasks, and which the exoskeleton might be expected to impact.

During farm and standardized task performance, farmers' workloads were measured using electromyography (EMG) to assess the activity of the lower back muscles and heart rate to assess physiological workload. . Standardized EMG measurements were summarized into 3 metrics: 1) static or low-level muscle activity; 2) median muscle activity which shows central tendency; 3) peak muscle activity. Following task performance, farmers participated in a semi-structured interview to explore

their experience with the exoskeleton and their perception of barriers and enablers of successful farm use. The quantitative sample was supplemented with 6 lab-based participants who performed only the standardized tasks.

RESULTS AND INTERPRETATION

When testing standardized tasks, we did not find any differences in low back muscle activity wearing the exoskeleton compared to not wearing it. However, all farm tasks showed some reduction when using the exoskeleton; these reductions were significant for static ($10^{th}$ percentile) and median ($50^{th}$ percentile) muscle loads. For the most difficult tasks, such as lifting bales, reductions were as high as 82% RVC (reference voluntary contraction).

We did not find any significant differences in heart rate variability while using the exoskeleton during standardized tasks. While it is possible that tasks with higher cardiovascular demand could show a difference, such tasks would be atypical in modern prairie farming.

Interviews with participating farmers yielded a framework of seven interrelated themes regarding exoskeleton use on farms: safety, mobility, comfort, ease of use, health, jobs & timing, and productivity. Farmers showed diversity in their perceptions of exoskeleton performance; depending on the person and task being evaluated, reports included high and low comfort, as well as negative, neutral, and positive productivity impacts.

After evaluating the exoskeleton in the farm context, we conclude that there is potential for a back-supporting exoskeleton to help reduce physical load to the low back on farms, particularly in reducing cumulative load over time. However, the degree of success will depend on an appropriate match between the exoskeleton, the farmer, and the task. At this stage, the evidence is mixed, and the knowledge base is not developed enough to recommend widespread use of exoskeletons on farms. The potential means that additional study is worthwhile; investigations with a broader range of participants, tasks, and including an economic analysis would help producers make informed decisions about implementing exoskeletons on their farms.

## Key Findings

- Muscle activity measures indicated that farm tasks required significantly less low back effort when using the exoskeleton
- Heart rate measures found the Use of exoskeleton had no significant impact on HRV
- Farmer interviews found that there are concerns with safety, comfort, and productivity when using the exoskeleton for certain tasks; for some combinations of people and tasks comfort and productivity ratings were high, indicating a need to tailor exoskeleton recommendations to the work tasks and context.
- Reducing physical load for the most demanding tasks could potentially extend farmers' productivity, particularly as women and older farmers form more of the workforce
- Although this study finds some potential in exoskeletons, additional research is required before broadly recommending their use on farms.

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## Abbreviations and Acronyms

EMG - electromyography

RVC – reference voluntary contraction

HR – heart rate

HRR – Heart Rate Reserve

MSD – Musculoskeletal disorders

CIHR – Canadian Institutes of Health Research

PAMI – Prairie Agricultural Machinery Institute

CASA – Canadian Agricultural Safety Association

AHSN – Agricultural Health and Safety Network (AHSN).

SAG –stakeholder advisory group

BMI – Body Mass Index

Hz – hertz

IQR – Interquartile range

NIOSH – National Institutes of Occupational Safety and Health

PREMUS – Prevention of Musculoskeletal Disorders triennial Congress

## Introduction

Musculoskeletal disorders (MSD) are more common among farmers (37.5%) (Rosecrance, Rodgers et al. 2006, McMillan, Trask et al. 2015); (Zeng, Kociolek et al. 2017) than in the overall workforce (17.6%); (Murray, Barber et al. 2015) MSD have been shown to impact not only health and quality of life of the workers, but also farm revenue (Coyte, Asche et al. 1998). In 2016, the one-year prevalence of musculoskeletal disorders (MSD) in Canada was 27% and the one-year prevalence of back pain was 12% (Trask, Bath et al. 2016). A previous study in the US Midwest, where geography and commodities are similar to the Canadian Prairies, showed farmers had double the risk of back pain compared to the general working population, and farmers were eight times more likely to make a significant change in their work activities due to back pain (Rosecrance, Rodgers et al. 2006). Farmer's MSD can limit their productivity and have economic impacts on a farm family; for example, farm income is lower when farmers have MSD-related disability (Whelan, Ruane et al. 2009). In addition to the high rates of MSD, farmers may encounter limitations to appropriate care due to their rural location. A recent qualitative study conducted on the Canadian Prairies reported that farmers' geographical isolation and heavy seasonal work demands combine to present barriers to care; long drives to receive specialized musculoskeletal care, lack of insurance coverage for non-physician care, and very long work days make self-management or adapted work tasks their preferred solutions (Bath, Jaindl et al. 2019).

Agricultural tasks frequently present ergonomic risk factors for MSD (Davis and Kotowski 2007); (Kirkhorn, Earle-Richardson et al. 2010), particularly sustained or repetitive awkward posture. The hierarchy of controls paradigm recommends the use of engineering controls that modify the tools or environment rather than personal protective equipment or training (Quinlan and Plog 2012). However, a change in work environment to reduce the exposure may not always be practical, especially when undertaking tasks at ground level such as calving or repairing fences since the ground height cannot be raised. Working at ground level can be accomplished using two main strategies: 1) stooping or bending over, and 2) squatting down to reach the ground (Fathallah 2010). Both strategies can lead to MSD risk. Prolonged back bending is known to contribute to the prevalence of back pain (Hoogendoorn, Bongers et al. 2000). Large cumulative exposures to deep knee flexion during squatting is related to increased risk of MSD in the lower limbs, particularly the knees (Reid, Bush et al. 2010). Thus, an engineering control to mitigate back pain in these work settings should, mitigate these exposures while still facilitating task performance at various heights, including ground level. One possible intervention strategy is to wear a supportive structure such as an exoskeleton.

An exoskeleton is a wearable device, a structure with linkage components mirroring the articulations of the lower limbs; the person who wears it is supported to sit or squat without excessive forces on their back or knees. The device is not fixed to a certain location but can rather be worn by any adult and used effectively throughout the workspace. In addition to a rigid-body linkage structure, the exoskeleton technology may include a passive mass-spring or pneumatic system, and an active robotic control (Bogue 2018). This technology has the potential to minimize, if not eliminate, awkward work postures and the associated MSD risk.

Although exoskeletons are currently used to reduce musculoskeletal exposures among assembly line workers in the manufacturing sector, the number of peer-reviewed studies on the industrial use of exoskeletons is limited, with most taking a perspective in mechatronics, not ergonomics. To our knowledge, there have been mostly laboratory studies investigating ergonomics of exoskeleton. For example, McGibbon, 2017 used motion analysis and a force plate to demonstrate the biomechanical load reduction while walking with an exoskeleton (McGibbon, Brandon et al. 2017). Using electromyography, Bosch et al. (2016) found a passive exoskeleton reduced back muscle activity in simulated industrial tasks by 35-38% (Bosch, van Eck et al. 2016). Despite the positive outcomes of those laboratory experiments, the development of the exoskeleton technology is still in its infancy, and it remains unknown whether they are suitable for reducing exposures related to MSD in agriculture.

Exoskeleton use is a growing area both in terms of research and commercially. There are several models currently available for purchase and marketing materials promote a mixture of production and safety benefits. Agriculture is a production-oriented and economically driven industry, and one where acquisition of new technology is generally motivated by enhanced production. It is important for new technology to be evaluated not only for these economic impacts, but also in terms of its impact on injury risk. For the exoskeleton, we anticipate a net benefit in terms of injury risk, with a reduction in biomechanical loads on the musculoskeletal system. However, it is possible that these benefits are more applicable to some tasks, and during other tasks like climbing ladders or working under vehicles the exoskeleton introduces new hazards such as contact stress or balance impairments. To address this, we tested the feasibility of this new technology in a variety of agricultural contexts and tasks, and to generate a list of decision points to consider when planning for exoskeleton use in agriculture.

The study of ergonomics resides at the intersection of human health and productivity; within the ergonomics paradigm, injury prevention and overall system performance have equal priority in design and evaluation. This makes ergonomics an appropriate lens through which to approach OHS within agriculture. One of the criticisms of the Enhanced Protection for Farm and Ranch Workers Act and the Fair and Family-friendly Workplaces Act is that they will impact the bottom line of small and medium farms. This view positions OHS as an expense and as an obstacle to profit and production, a common attitude but one which prevents adoption of a progressive safety culture. The benefit of adopting an ergonomics paradigm for evaluating workplace technologies in Alberta agriculture is in reinforcing the connection between the complementary priorities of productivity and health. MSD and particularly back pain is common in prairie farmers, and 57% farmers report these types of injuries impacting their work tasks and quality of life (McMillan, Trask et al. 2015). When an injury prevention strategy is shown to contribute to productivity in addition to reducing the revenue impacts of absenteeism (or ‘presenteeism’, characterized by reduced productivity while at work), it aligns with producers’ priorities and becomes desirable rather than resisted.

According to the 2016 Canadian Agricultural census, there are 40,638 farms in Alberta; agriculture is a historically and economically important industry to the province. The climate, geography/topography, commodities and farm practices are very similar between Alberta and neighboring Saskatchewan. We propose to conduct this study in Saskatchewan in order to efficiently leverage the existing network of producers to participate in the field trials; it would cost far more in dollars and time to recruit, schedule, and travel to Alberta farms for this research. However, we anticipate that similarities between the two provinces would generate comparable results. The agricultural census confirms similar workforce trends in terms of aging; the average age of Alberta farm operators is 55.7 years compared to Saskatchewan’s 55.0 years. Farms are also very similar in size, both being larger than the Canadian average; farm size averages 1237 acres in Alberta compared to 1784 in Saskatchewan. They also share common commodities, and with that come common farm practices. Alberta and Saskatchewan have the first and second largest beef herds in Canada, and the top two field crops in both provinces are Canola and spring wheat. The similarity in industry and workforce between the two provinces, combined with incorporation of Alberta-based partners on the study team, will make this study relevant, applicable and usable for Alberta workers.

This research will inform future improvements in farmers' health and productivity by delivering findings on multiple aspects of exoskeleton ergonomics. The results will help researchers, manufacturers, and other stakeholders understand potential facilitators for, and barriers to, farmers' adoption of such devices. We plan to deliver fact sheets that will help farmers themselves make informed decisions about exoskeleton use on farms. In the future, this research could be expanded from a preventive solution for actively working farmers to an intervention that helps injured farmers to return to work.

## Study Objectives

While sustainability of the agricultural workforce in Alberta is threatened by the high prevalence of MSD, developing effective interventions to reduce the burden of MSD within the farming context will contribute to the long-term health and productivity of farm workers. This field-based project will be among the first to establish a foundational understanding of farmers' biomechanics and experience when using an exoskeleton to perform tasks. In other words, it will address the aforementioned gaps with field testing, and provide a multi-disciplinary ergonomic evaluation of a prototype exoskeleton to determine suitability as a preventive device for MSD among farmers. This study aimed to deliver findings on multiple aspects of exoskeleton ergonomics and to help agricultural stakeholders understand what the potential facilitators and barriers to farmers' adoption of the exoskeleton devices might be.

# Methodology

## Stakeholder Advisory Group

To ensure that the results of this study remain relevant to the industry, the research team recruited and maintained strong industry connections through the use of CIHR's integrated knowledge translation (KT) approach, engaging stakeholders throughout the research process (CIHR 2012). Forming partnerships with key stakeholders was intended to produce results that are more relevant and more likely to be put into practice. This study involved collaborative interaction between decision-makers and researchers that resulted in mutual learning through the process of planning, producing, disseminating, and applying existing or new research in decision-making.

The original grant proposal was developed in collaboration with industrial partners from the Prairie Agricultural Machinery Institute (PAMI), the Canadian Agricultural Safety Association (CASA) and the Agricultural Health and Safety Network (AHSN). A full list of the SAG members and their affiliations is provided in the acknowledgments section.

In addition to specific input during grant development, several representatives from Alberta and Saskatchewan were invited to form a stakeholder advisory group (SAG) to help inform and guide key stages in the research process. The SAG participated in two meetings:

1. Initial planning meeting to get input on project goals and parameters, discuss exoskeleton selection and methodology, and to ensure stakeholder needs were addressed
2. Post-data collection meeting to present preliminary findings, invite stakeholder interpretations, and co-create dissemination plans

## Study design

This study started with a heuristic pilot tasked intended to identify an exoskeleton appropriate for farm work. The subsequent cross-sectional, mixed methods study had both lab- and field-based components. The field-based phase is a mixed-methods evaluation consisting of both quasi-experimental comparison of task performance with and without the exoskeleton and an interview of farmer experiences with the exoskeleton.

## Heuristic Pilot: Selecting the Exoskeleton and Farm Tasks

This study evaluated a single exoskeleton, and the selection was based on a high degree of match between the specifications of several models and anticipated performance with the selected 'candidate' farm tasks. The general criteria for exoskeleton suitability was for it to show good alignment between the listed specifications/function and the work demands, i.e. the most frequent non-neutral postures and/or manual handling tasks. Previously-recorded video of farm tasks common on the Canadian Prairies were reviewed to assess alignment with two models of exoskeleton. It was determined that a passive exoskeleton (i.e. with neither motor nor actuator) would be more economically feasible on prairie farms, and more practical when working far from a power source. A simplified example of a heuristic matrix summarizing the matching of video recorded farm tasks and exoskeleton performance is shown in Table 1.

Table 1: Example heuristic matrix summarizing farm task demands and exoskeleton characteristics

| **Task** | **Manual handling** | **Frequent Posture** | **Range of motion** | **Exoskeleton Suitability** | |
|---|---|---|---|---|---|
| | | | | **Model 1** | **Model 2** |
| Piglet vaccines | Minimal | Bending forward | Back bending 0°-70° | Yes, change posture to supported squatting or sitting | Yes, back is supported while bending |
| | | Kneeling | Knee flexion 90°-135° | No, not within the range of motion the exoskeleton allows | No, not in body region that is supported |
| Fence repairing | No | Bending forward | Back bending 0°-70° | Yes, change posture to supported squatting or sitting | Yes, back is supported while bending |
| | | Kneeling | Knee flexion 90°-135° | No, not within the range of motion the exoskeleton allows | No, not in body region that is supported |
| Calving | Yes | Bending forward | Back bending 0°-60° | Yes, change posture to squatting for lifting or lowering | Yes, back is supported while bending to lift |
| | | Squatting | Knee flexion 20°-90° | Yes, the squatting or sitting within this range is supported | Yes, squatting is permitted but not supported |

The stakeholder advisory group reviewed the selected tasks for the representativeness to manual farm activities in Canadian Prairies. Stakeholders were also presented with the heuristic matrix that compared the participant tasks with the exoskeleton options, and asked to provide input on the final exoskeleton selection. This heuristic pilot resulted in the selection of a passive (i.e. non-powered) back-supporting exoskeleton produced by Laevo, as shown in Figure 1.

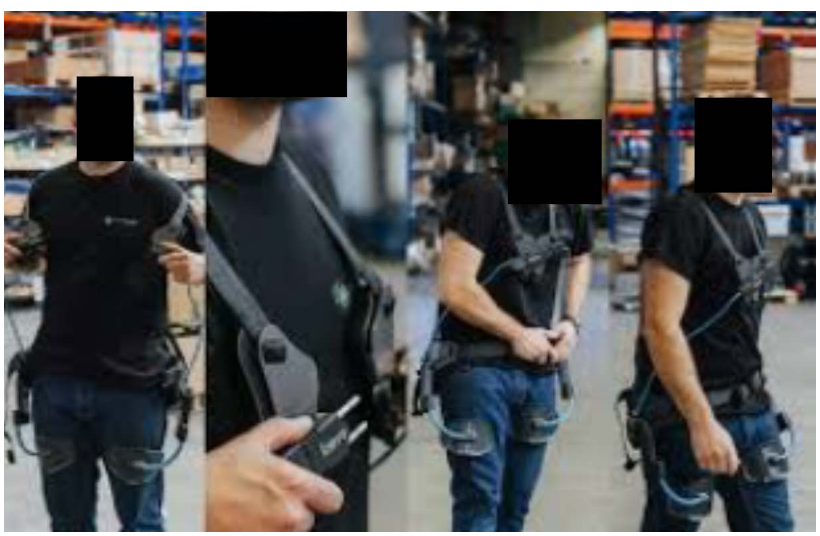

*Figure 1: Laevo V2.5, Laevo Exoskelet, Delft, the Netherland Laevo exoskeleton*

## Participant Recruitment

There were two types of participants in this study: farm-based to test the exoskeleton on real farm contexts with ecological validity, and lab-based to expand the sample of standardized tasks for statistical comparisons. Lab-based participants (n = 6) were recruited from the university community to perform a series of standardised tasks. All participants were female, age 28 (SD=5) years old, 164 (SD=4) cm in height, 54 (SD=8) kg in weight, BMI 20.06 (SD=2.25).

We completed visits at 12 farm worksites; where possible, we collected data from more than 1 participant per farm. The field trials were conducted on 15 healthy active farmers in Saskatchewan. A convenience sample of adult farmers, were recruited from farm trade shows, previous agriculture research networks (McMillan, Trask et al. 2015, Zeng, Kociolek et al. 2017), and through the University of Saskatchewan agricultural commodity units. An informative postal package was sent to all potential participants, followed by telephone call to determine eligibility, then scheduling and planning farm visit. Eligible participants had no known health conditions that could prevent them from safely using the exoskeleton. Farmers averaged 176 (SD=6) cm tall, mass of 80 (SD=13) kg, BMI 26.56 (SD=4.4) and had 23 (SD=17) years of experience; additional characteristics are reported in Table 2.


*Figure 2: Research team members help a farmer to put on the exoskeleton. Photo by Wiliam Dekay*

Farm visits were scheduled to capture the tasks identified during the heuristic task identification phase; see Table 2 for a description of tasks performed. Farmers performed the standardized tests in the same way as the lab-based participants (see Figure 3). A quasi-experimental approach was used to evaluate up to an hour of task performance with and without the exoskeleton. Tasks were performed within the farm environment, at the farmer’s own pace, and with their usual tools and materials. At the end of the experiment, farmers were asked to complete a short survey followed by an interview about their experience using the exoskeleton for minimum of 60 minutes. This was used to evaluate productivity, feasibility, and user experience.

Table 2: Characteristics of farmer participants and description of farm tasks performed during the farm-based field tests

| ID | Farmer Characteristics | Farm Task Performed |
|---|---|---|
| 1 | Male, aged 66 to 70, mixed farm owner | In barn:<br>shoveling manure and hay from the ground and throwing them overhead onto a cart |
| 2 | Male, aged 41 to 45, grain farm owner | Outdoor:<br>a) clearing metal boxes around work area using the forklift/wheel loader<br>b) repair work on combine machine with arms raised slightly above head |
| 3 | Male, aged 56 to 60, grain farm owner | Outdoor:<br>a) cutting/sawing timber using chainsaw<br>b) loading/moving timber using tractor |
| 4 | Male, aged 51 to 55, mixed farm owner | Outdoor:<br>a) lifting and aligning fence posts on ground from picket fencing machine<br>b) lifting rectangular bales of silage (approx. 60 to 70lb) between shed and tractor<br>Indoor:<br>lifting 20 rectangular bales from tractor and arranging them in the barn |
| 5 | Male, aged 56 to 60, grain farm employee | In grain bin:<br>shoveling grain/oilseeds from bin into machine for transport |
| 6 | Male, aged 56 to 60, grain farm owner | In grain bin:<br>shoveling grain/oilseeds from bin into machine for transport<br>*task involved many movements in and out of the grain bin and operating truck for loading grain |
| 7 | Male, aged 51 to 55, grain farm employee | In grain bin:<br>shoveling grain/oilseeds from bin into machine for transport |
| 8 | Male, aged 26 to 30, mixed farm employee | In workshop:<br>grinding fence post (stooped using a grinder to trim metal poles) |
| 9 | Male, aged 31 to 35, grain farm employee | Outdoor:<br>front loader – digging clearing farmland |
| 10 | Male, aged 31 to 35, grain farm employee | Outdoor:<br>excavator – mixing/filling soil and leveling |
| 11 | Male, aged 36 to 40, grain farm employee | Outdoor:<br>repair work on truck's tires primarily (squatting, standing and walking around) |
| 12 | Male, aged 56 to 60, grain farm owner | In grain bin:<br>shoveling grain/oilseeds from bin into machine for transport |
| 13 | Female, aged 56 to 60, mixed farm owner | Outdoor:<br>a) shoveling of spilled grain into bucket for chicken feed<br>b) transporting buckets of grain with a quad bike into the barn<br>c) stooped to catch poultry<br>d) fence repair using a sledgehammer |
| 14 | Male, aged 51 to 55, poultry farm employee | In barn:<br>a) moving feed bags and emptying into bucket<br>b) collecting eggs into crate and arranging on the cart |
| 15 | Male, aged 51 to 55, poultry farm employee | In barn:<br>a) Moving feed bags and emptying into bucket<br>b) Collecting eggs into crate and arranging on the cart |

## Measurements

This study completed three main data collection measures: inertial sensors to measure the back and lower limb postures, electromyography (EMG) to measure muscle activity, and heart rate monitors to estimate metabolic energy expenditure.

### Muscle Activity

Erector spinae muscle loading was assessed using surface electromyography (sEMG). Bipolar surface electrodes with a fixed inter-electrode distance of 20 mm (SX-230-1000, Biometrics Ltd., Newport, UK) will be vertically placed at 35 mm lateral from lumbar spine L1 on both left and right sides (Figure 2). The sEMG were collected with portable data-logger (MWX8, Biometrics Ltd.) and digitally stored to a microSD card at 1,000 Hz. The EMG signal was low pass filtered at 10 Hz using 2nd order Butterworth filter.


*Figure 3: A farmer (R) lifts a box during the repetitive lifting standardized task while wearing the exoskeleton. Photo by William Dekay.*

To allow comparisons among participants and study conditions, collected EMG was normalized to maximum voluntary efforts. At the beginning of work shift, participants were asked to perform and sustain three 5-second maximum voluntary contractions (MVC) with 2 minutes rest between each contraction. During the MVC, the participants lay on their front and applied maximum trunk extension without using upper or lower limbs against external load. Normalized EMG were summarized using amplitude probability distribution function (APDF); the 10th, 50th and 90th percentiles of EMG represent static, median, and peak muscle activity.

Exoskeleton and non-exoskeleton conditions were compared across each standardizes task using the non-parametric Wilcoxon Signed-rank tests. After log-transforming the EMG variables, comparisons across all farm tasks were performed using generalized linear models with ‘participant’ and ‘task’ as a random effects.

## Heart rate and physiological workload

Heart rate data was successfully collected for 18 participants (5 female lab-based, 13 male farm-based) with median age of 51 year (Interquartile range, IQR=26.8) and BMI of 23.9kg/m$^2$ (IQR=7.9). Participants wore a heart rate monitor (Actiheart, CamNtech, Bio-Lynx Scientific Equipment Inc., Montreal, Quebec, Canada) on two EKG electrodes throughout the task performances to allow comparison of energy expenditure with and without exoskeleton use. Heart rate data was analyzed only during the three simulated tasks of symmetric lifting, asymmetric lifting, and static bending.

Heart rate reserve (HRR) was calculated in order to assess physiological workload or task intensity. HRR has been used since the 1950s to assess the intensity of activities in a way that accounts for participants' ages and fitness levels; it is calculated using the difference between a person's age-predicted maximum heart rate and their resting heart rate. In this study we calculated task intensity as a percentage of heart rate reserve (%HRR). Resting heart rate was recorded from each participant after several minutes of quiet sitting. Percentage heart rate reserve was then calculated as:

$$HRR = \frac{HR_{task} - HR_{rest}}{HR_{max} - HR_{rest}}$$

Differences in %HRR between the "with" and "without" exoskeleton conditions were made using paired t-tests for each task.

## Interviews with Farmers

This was followed by interviews to assess participants' experiences during the test, including any suggested improvements or changes to body comfort, work technique, productivity, as well as the feasibility of the device on their farm. In addition to immediate experience with the exoskeleton, they were also asked about potential barriers or facilitators to use on their farm that were not present during the trial.

The face-to-face, semi-structured, one-on-one interviews of 10 to 35 minutes per participant were audio-recorded at each farm site. The attached interview guide contains questions and prompts used for collection of in-depth information on perceived impacts on changes to overall work behaviors, performance, productivity, perceived feasibility, potential utilization of the exoskeleton for the tested tasks and any other relevant tasks, strengths and limitations of the device, satisfaction with the device and a 'wish list' of any improvements to the device. Participants were also asked to speculate on potential impacts on musculoskeletal health, prioritization of exoskeleton purchase when allocating resources for farm equipment, and barriers or facilitators for exoskeleton use among themselves and other producers in their network.

A qualitative descriptive phenomenological approach was used, for asking participants to comparatively describe and evaluate each event, activity, or phenomenon based on their experience in completing their tasks while wearing the exoskeleton.

The audio-recorded interviews were transcribed verbatim and analyzed using NVivo v12 qualitative analysis software (QSR International, Melbourne Australia). The research team performed a continuous and iterative analysis of the transcripts to highlight quotes and code them inductively based on research questions. Codes were refined by discussion and consensus during team meetings; then consolidated into themes and related to core research questions.

# Results and Interpretation

## EMG Findings

### Muscle activity during standardized tasks

Exoskeleton use did not significantly change any muscle activity measures when participants performed the standardized tasks. However, there were some trends worthy of further research. Exoskeleton use tended to decrease only the median and peak muscle activity but increase static muscle activity.
The standardized lifting tasks were designed within NIOSH lifting equation specifications intended to protect most workers, so most participants were working well below their maximum capacity. We did a visual pattern inspection to investigate whether personal characteristics (regular physical activity level, age, sex and BMI) impacted the effect of exoskeleton, but no meaningful patterns were identified in the combined lab-based and farm-based sample size of 20.

### EMG Result: Muscle Activity during Farm tasks

Exoskeleton use reduced muscle activity during all measured farm activities. When all farm tasks were combined, these reductions were statistically significant only for static and median muscle loads (see Figure 4).

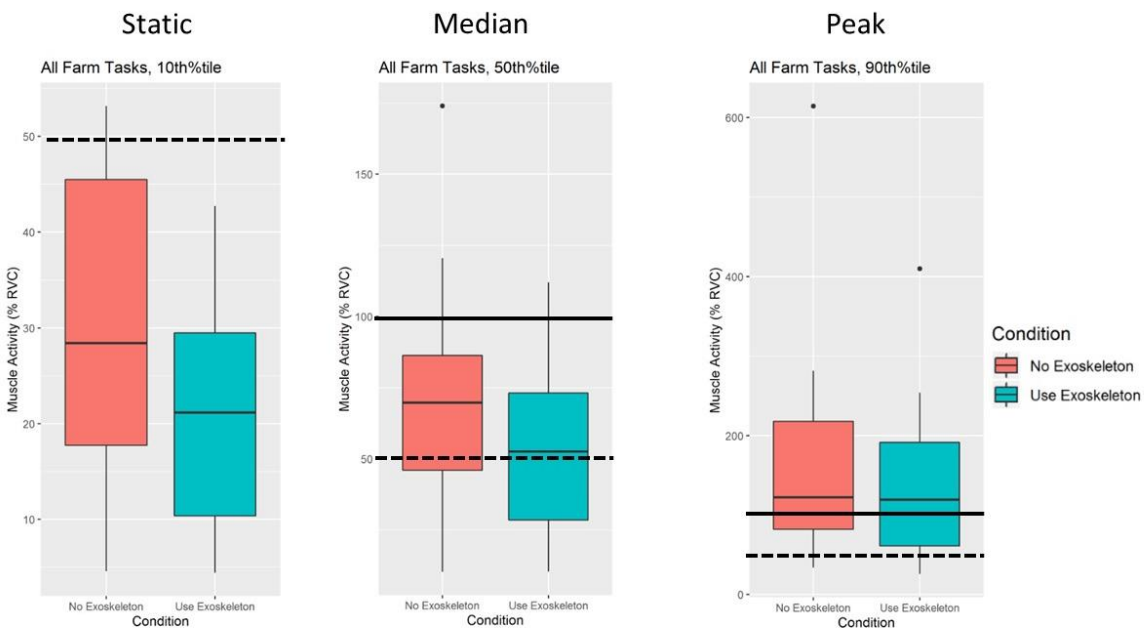


*Figure 4: : Low back muscle activity with (turquoise) and without (coral) the exoskeleton, reported as static (10th percentile, L) median (central tendency, middle) and peak (90th percentile, R). Both static and median muscle activity were significantly lower with the exoskeleton. Note that each panel uses a different scale, the dotted black line represents half of the muscular effort of the reference contraction, the solid black line represents the reference muscular effort of the reference.*

In the low activity grouping of muscle recruitment some farm tasks showed a larger reduction in back muscle activity than others. A 29 % reduction in static muscle activity was seen in the 'catching poultry' task. In contrast, another flexed task described as 'grinding fence post' demonstrated very little reduction (0.2 %) in static muscle activity. Other tasks with a mix of some flexed posture and manual material handling, including ‘shoveling manure’, ‘shoveling grain’, and ‘collecting eggs’, demonstrated moderate (7% to 16%) reductions in static muscle activity.  Although the ‘front loader operation’ task, involving sitting on machinery and using arms to operate machinery, demonstrated a promising 12% decrease in static muscle activity we do not recommend use of the exoskeleton during machinery operation. A lack of match between tool and task was previously identified in the heuristic review, by other researchers (Upasani, Franco et al. 2019), and also in the interviews with farmers in this study (see below).  During our field testing, machinery use was nonetheless included in the study because farm tasks varied unpredictably throughout the day and farmers were performing real tasks during the study, not directed by the researchers.

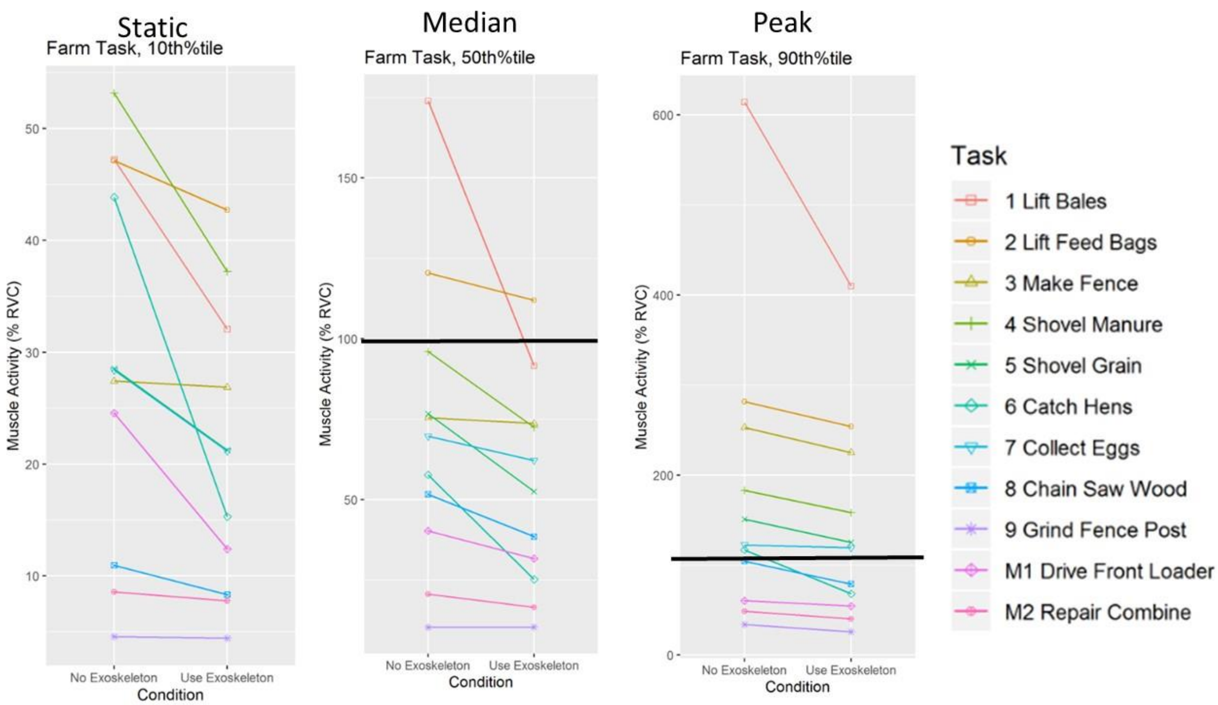


*Figure 5: The static (10th percentile, Left panel) median (central tendency, middle panel) and peak (90th percentile, Right panel) low back muscle activity during several typical farm tasks with and without the exoskeleton (left and right of each panel, respectively).  Note that each panel uses a different scale; the solid black line represents the reference muscular effort of the reference.*

For moderate levels of muscle activity considerable reductions in muscle activity were observed as high as 82% for ‘lifting bales’, (heaviest loads of all the tasks).  The second largest decrease (32%) in muscle activity also occurred during ‘catching poultry’ task and two shoveling tasks, which involved both bending and force exertion, also had substantial reductions of 24 %. Finally, exoskeleton use moderately reduced the median muscle activity for the ‘chain-sawing wood’ task by 13 %RVC.
During the generation of peak muscle activity reductions in muscle activity ranged from 3 to 205 %. Similar to moderate levels of muscle activity, peak muscle activity showed the greatest reductions while ‘lifting bales’, followed by ‘catching poultry’ as well as ‘lifting feed bags’, ‘building fences’, ‘chain-sawing wood’ and two shoveling tasks.

## Heart Rate Findings

Heart rate measurements with and without the exoskeleton for all 3 standardized tasks are shown in Figure 6. Although lower HRR values were observed when using the exoskeleton, results of the paired t-test showed no significant differences in %HRR (p = 0.06, 0.24, and 0.50 for standardized tasks 1, 2, and 3 respectively).

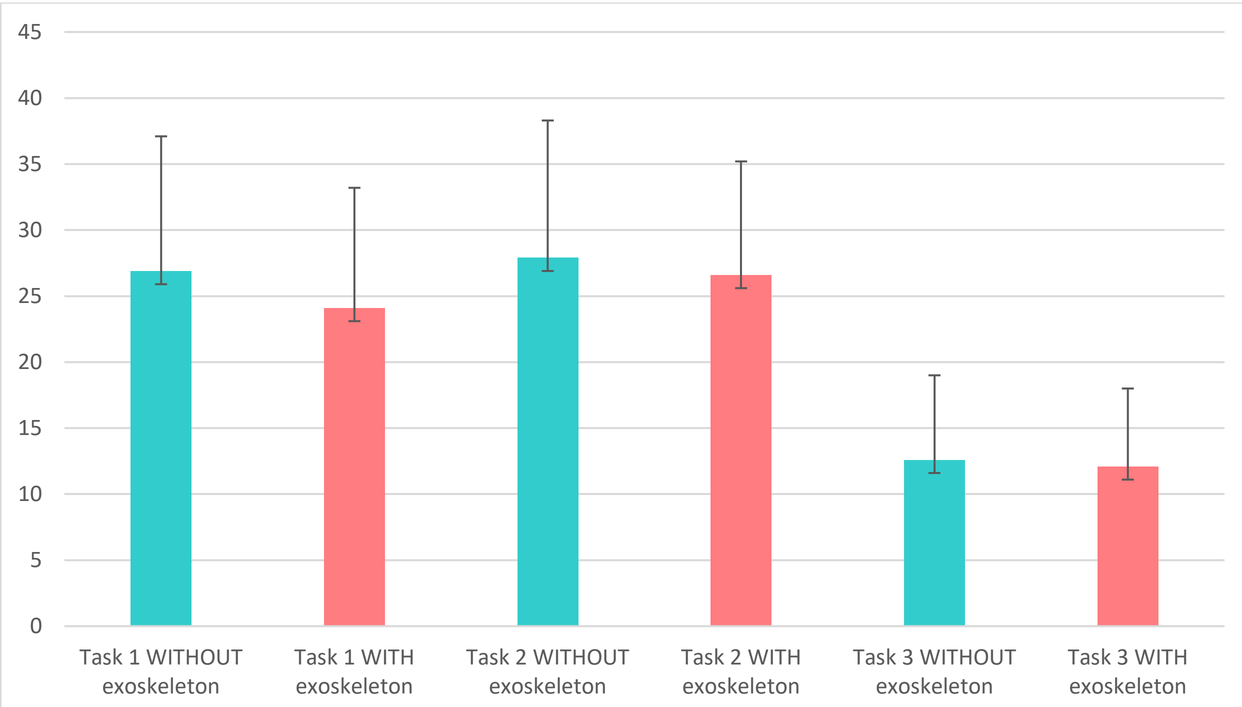


*Figure 6: Mean percentage heart rate reserve (%HRR) in beats per minute (bpm) without the exoskeleton (turquoise) and with the exoskeleton (coral).For 3 standardized tasks: 1) symmetric lifting; 2) asymmetric lifting and 3) sustained bending. Whiskers indicate standard deviations. No significant differences were found between the 'with' and 'without' exoskeleton conditions.*

## Interviews: Farmers' Perceptions of Exoskeletons for Farm Tasks

Interviews with study participants showed diversity in farmers' perceptions of exoskeleton performance. Figure 6 illustrates farmers experiences and perceptions within a framework of seven interrelated themes: safety, mobility, comfort, ease of use, health, jobs & timing, and productivity.

Each interconnected theme demonstrated a mix of exoskeleton advantages and disadvantages, depending on the farmer and the task. For example, within the theme 'health', some participants described the benefits of exoskeleton use in terms of feeling more support or facilitating better posture; on a contrary, others who described having good back did not perceive these long-term health benefits. Within the theme of 'productivity', some described being able to accomplish more shoveling work faster with less energy, while others felt encumbered by tension in leg pads while walking. The degree to which exoskeleton use helped or hindered may relate less to its intrinsic design properties and more to characteristics of the farmers and tasks.

**Exoskeleton Advantages**

*"…I feel much [more] comfortable lifting things up and putting them down. I don't know, it's like it's helping – helps support the body – that's what I feel."*

Age, sex, and other user characteristics may impact the success of exoskeleton use during farm tasks. The present study included only one female participant, but it is worth noting that some of the fit and pressure point concerns raised specifically related to female body shape. It will be important to conduct further testing on women to ensure that the exoskeleton can work for all farmers. It was also noted that older farmers (≥ 49 years) tended to report the device being supportive, while younger farmers (< 49 years) tended to report it was not restrictive enough.

**Exoskeleton Disadvantages**

*"The clumsiness for getting in, say a motor vehicle or a tractor or something, it's a little bit bulky, but you'd get used to it if you wore it I think. Like I seem to do fine there this morning with it."*

Exoskeleton use tended to be described as helpful in tasks that involved bent or stooped postures, lifting, and repetitive motions, including: shoveling, lifting, grinding metal, cutting/slicing wood at ground-level, fencing, and collecting poultry/eggs. Alternatively, exoskeleton use while driving or operating farm machinery was often described as an encumbrance; the intended design of the exoskeleton was unlikely to offer appropriate support during prolonged driving tasks.

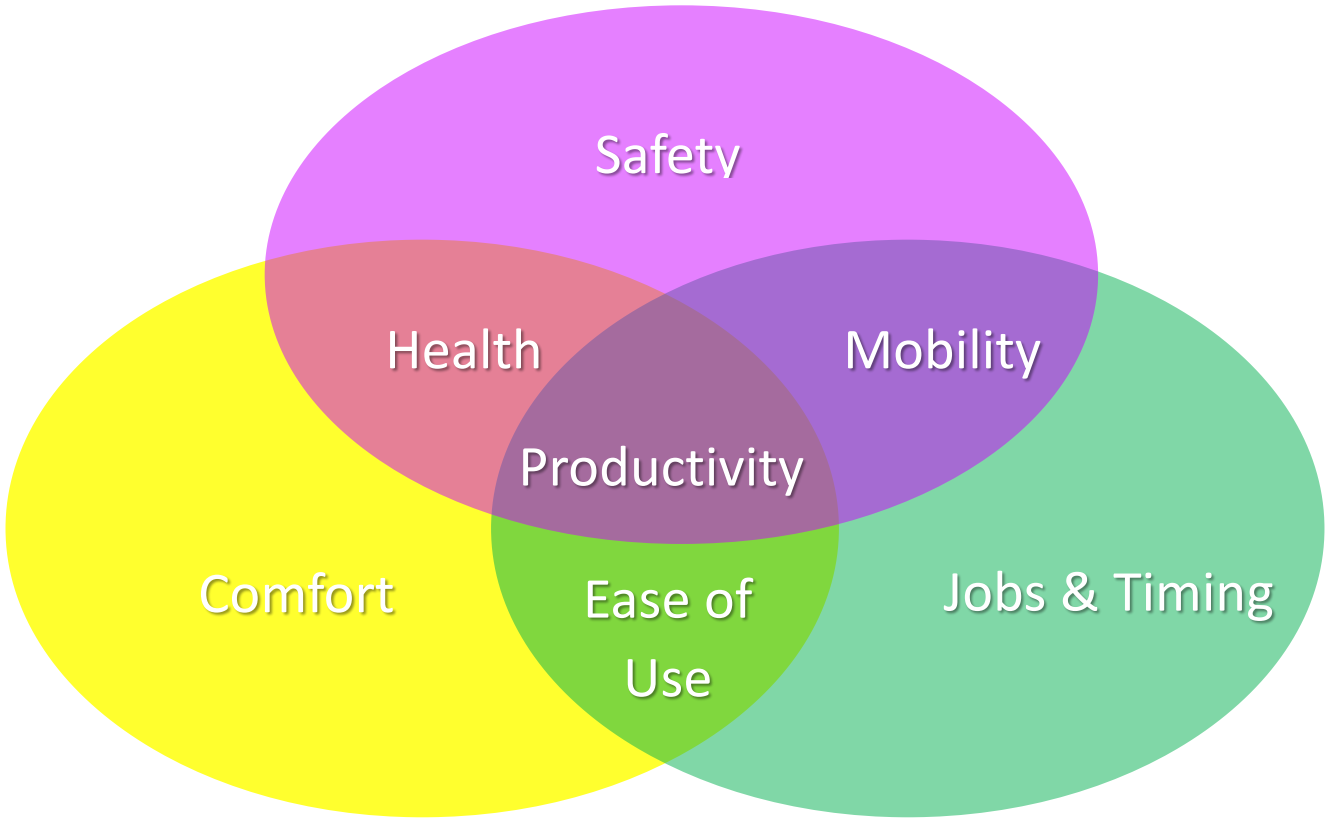


*Figure 7: Interconnected themes describing farmers' experience with exoskeleton use for farm tasks, emerging from interviews*

Table 3: Quotes from farmers who participated in the exoskeleton trial describing their views on suitability of exoskeletons for various farm tasks:

| Task | Quotes promoting use/ PROs | Quotes discouraging use/ CONs |
|---|---|---|
| Getting in /out farm machinery or grain bin door | *None* | *"The only time I even had an issue with it was just getting in and out of the cab, the cab's kind of a little tight squeeze getting in"*<br><br>*"It was, like yeah like when I was kind of getting in and out it was restrictive but as for actually moving around in that. That was the one time where I had an issue…. the only time I ever had an issue was just getting in and out of the wheel loader."* |
| Shoveling grain | *"I think my back feels quite a bit better after shoveling that long, like without that, I'd probably, my lower back would be sore."* | *"It did restrict me a little bit up on top of the neck, when I was shoveling but it wasn't bad, but otherwise it wasn't…. just that it was pulling a little bit on my neck, right in here."* |
| Lifting bales, animal feeds or woods | *"I guess there were a couple of times that I felt that I was stronger because of the assistance the spring was giving me…"*<br><br>*"When it would come down to lifting things, lifting and placing onto shelving, stuff like that, it would definitely help over a time period if you were to be doing it on a steady basis – it would definitely help."* | *None* |
| Prolonged bending task | *"I really felt it when I wasn't wearing it once I got back up. Obviously, being bent over for ten minutes or so it's a bit sort of wearing on the back as well because I'm grinding and moving back and forward quite a bit, but basically very little of that when I was wearing the exoskeleton."* | *None* |
| Poultry farming | *"I think for doing certain activities, yes, I would like it, you know, when we're feeding in the barn, picking up the bags and feeding, I would love it for that. And when we're shoveling out in the barn, pushing on the barn, it'd probably be a help there… but again when we're loading the eggs from the cart on to the pallet you're picking up 180 eggs, so there's quite a bit of picking and twisting there, so it would be, it would help there I think."* | *None* |
| Cutting log of wood with chainsaw | *"I liked it for getting up and down – it helped me get up. Like, it was half the effort to get up, and that's where I get sore is when I'm bending down, getting back up. Especially if you get a load of wood in your arm or whatever when you're down there."* | *None* |
| Fencing using a sledgehammer | *"It was a little tough at first, but then after when I started swinging, it was okay. Like it was fitted nice too, and around the neck and everything and it wasn't pulling as much when I was hammering than when I was shoveling."* | *None* |
| Farm machinery repair work | *None* | *"In a bit it does, it is bulky. It is. It's a thing I would definitely would not be able to wear for what my job is because it would be a danger hazard – especially around moving parts, moving pieces – it would be a hooking hazard."* |
| Climbing e.g. grain bin | *None* | *"Except when I was climbing some stuff, you know, it was sticking out so it'd be - liable to catch on something."* |
| Carpentry work | *"Well maybe for, I don't know, it's hard to say. Maybe carpentry kind of work. We always got buildings to fix and stuff, and maybe it would fit in better there, 'cause you're always bearing a lot of weight when you're doing that stuff, right?"* | *None* |
| Clearing land manually | *"But there's other jobs (exoskeleton) would work for too….Like take the bush out and all the stumps and roots."* | *None* |

# Implications and Applications

## Implications of the EMG Findings: Muscle load in relation to risks of low back pain

In this study, we used EMG as a proxy measure for low back load, and it should be noted that this cross-sectional study cannot determine whether decreasing back muscle activity by the observed amount would reduce risk of low back pain over the long term. In our interpretation we are presuming that low back pain develops as a result of cumulative physical exposure over time, and that even small reductions in a repetitive task could add up over a day, year, or working lifetime.

Although not statistically significant, the 8% decrease in median muscle activity (from 116 %RVC to 108 %RVC) observed during standardized repetitive lifting could possibly lead to reduced cumulative exposure and associated risk of back pain. On the other hand, during asymmetric lifting the median muscle activity was essentially the same regardless of exoskeleton use (104 %RVC and 105 %RVC for working without and with the exoskeleton), suggesting that use of an exoskeleton may not help much when repetitive lifting is asymmetric. One reason why the exoskeleton was less effective in standardized tasks than in farm tasks may be that participants performed standardized tasks for a very short time (approx. 3 minutes) This condition was different from farm tasks, where participants had more time to trial work strategies while wearing the exoskeleton, and may have adopted more optimal postures to accomplish the tasks during the 10-30 minutes of the trials.

## Implications of the Heart Rate Findings: Impact of Exoskeleton on Workload

We found no significant differences in %HRR when using the exoskeleton. The standardized tasks were designed to incorporate many of the back-intensive demands of farm tasks, but it may be that they were not highly demanding on the cardiovascular system. The lifting tasks required, on average, around a quarter of heart-rate reserve and an eighth of the static bending tasks. It may be that other sustained tasks requiring a higher %HRR would be required to detect a potential impact from the exoskeleton.

## Implications of the Interview Findings: Usability of Exoskeletons on Farms

Farmers' experiences relate that exoskeletons may not be compatible with all types of farm tasks. The farm workplace environment, conditions, and modes of operation as well as the individual's characteristics will be key to successful use on farms. Equipment-based preventive interventions in the workplace have been shown to be dependent on both individual and environmental factors, with environmental factors considered most important (Koppelaar, Knibbe et al. 2009).

Although there has not been much research investigating farmers' perspectives with exoskeletons, our findings are consistent with an American survey of agricultural safety and rehabilitation service providers, (Upasani, Franco et al. 2019). That study also identified a need for compatibility with work clothes, for device flexibility across multiple farm tasks, and ease of fitting and removal. Similar safety concerns included the device getting caught on sharp edges, moving parts, or power take-off, clearance issues in narrow passages or between equipment, climbing up and down grain bins or machinery, and concerns over exoskeletons conducting electricity. Beyond the farm environment, an overview of occupational exoskeletons recommended integrating workplace safety and risk management into exoskeleton design, emphasizing consideration of health and safety (van der Vorm, Nugent et al. 2015), in addition to the same usability criteria found in the current study and the American farm exoskeleton study.

Farmers in our study also prioritized productivity; this also echoed the findings from the American study where exoskeleton use was described as something that could 'demonstrate its value' by providing farmers with a 'competitive edge' (Upasani, Franco et al. 2019). The importance of farmers cost-benefit evaluations should not be underestimated. This study did not ask participants specifically about cost, but it is known it is of vital importance when producers consider interventions (Douphrate and Rosecrance 2004, Mokarami, Varmazyar et al. 2019). Integration of exoskeletons could increase productivity, though this must be balanced with the exoskeleton purchase up to several thousand dollars (a substantial investment for a small owner-operated enterprise). While there is evidence that injury prevention strategies that contribute to productivity and align with producers' priorities become desirable rather than resisted (Bertera 1990, Martimo, Shiri et al. 2010), it remains to be seen if the productivity benefits of the exoskeleton outweigh the cost of initial purchase, maintenance, and any administrative scheduling demands.

## Strengths and Limitations

To our knowledge, this is the first field trial exploring the use of back-supporting exoskeletons in the agricultural industry. Therefore, the primary contribution of this relatively small exploratory study is in providing the first reports of directly measured physical exposure as well as farmers' perceptions.

The study also has some limitations which should be considered when interpreting the results. The relatively small sample size precluded adequately-powered statistical investigation of multiple covariates like participant characteristics when comparing the effect on physical exposures. The convenience sampling approach also carries risk of bias, since those who consistently participate in health and safety research are more likely to feel favourably towards health and safety interventions; the farm sample also skewed male and did not include all Canadian commodity types. Although not considered representative, our study captured a more diverse population than previously published exoskeleton research. More than half of the participants were older than 50 years, and when the lab-based participants are included there are more women than have been included in much of the previous research. However, the small and unrepresentative sample size is not as limiting for the interview study, which took a qualitative approach focusing on richness and depth rather than generalizability. The contribution of the interviews is in understanding the feasibility of exoskeletons in a real-world farming context based on the perspective of working farmers and understanding barriers and enablers of farm use.

While this study investigates potential barriers and facilitators to real-world use on farms, the farmers had a relatively short amount of time to use the device, and thus some long-term benefits (e.g. back pain) and long-term problems (e.g. maintenance or job planning) were likely not identified during one day on the farm. The study also did not attempt an economic evaluation, which is important when determining adoption of new technology. Longer term trials of workplace effectiveness including economic evaluations are still needed.

## Knowledge Translation Summary

In addition to the Stakeholder Advisory Group which contributed to the integrated Knowledge Transfer and Exchange approach adopted in this study, study findings were disseminated to the farm and research communities in several ways:

- This report and the accompanying data library delivered to the Alberta OSH Futures program.
- Displayed the exoskeleton and promoted the study at farm trade shows, including the Farm Progress Show June 19-21, 2019. In addition to assisting with recruitment for the study, this provided an opportunity for farm operators to encounter the technology, including several who tried it on.
- A study website hosted by the University of Saskatchewan Ergonomics Lab: https://research-groups.usask.ca/ergolab/our-research/exoskeleton.php
- We have engaged with the University of Saskatchewan media productions department to develop a video summarizing the main findings of the study. This avenue for dissemination was suggested by the Stakeholder Advisory Group as something that would be accessible and engaging for farmers. Once complete it will be available on YouTube; we are currently awaiting production to continue following COVID-19 distancing guidelines.
- A lay article describing study results will be sent out to Saskatchewan farm families in a semi-annual newsletter by the Agricultural Health and Safety Network; we are anticipating delivery in the Autumn of 2020.
- This work has been presented at National scientific conferences, including the Canadian Agricultural Health and Safety Association (CASA), as well as internationally at the Prevention of Musculoskeletal Disorders triennial Congress (PREMUS).
- At the time of submitting this report, two research articles have been submitted for peer-review in scientific journals. We anticipate these will be published and available to the scientific community in the coming months.

## Recommendations for Future Studies

Although this study has made an important contribution, there are still many questions left unanswered, that can be addressed in future studies.

- This study had a more diverse sample than much of the published exoskeleton studies so far, there is a lot of work to do in terms of collecting results for diverse populations. For example, older workers and women should be prioritized in future studies since they are more likely to benefit from the support during demanding tasks potentially provided by an exoskeleton.
- Intensive agricultural sectors such as confined animal feed operations may have many heavy and repetitive tasks that are performed consistently in all seasons; future studies could investigate exoskeleton use in pork production, cattle feedlots, and dairy.
- Widespread and practical use on farms will require addressing safety concerns related to farm equipment and tasks; for example, getting caught on moving machinery, climbing grain bins, walking distances and operating machinery.
- Although we found some impact on muscle activity particularly among lifting tasks, future studies can include tasks with a high cardiovascular demand to investigate the impact of the exoskeleton on physiological workload.

- Longer term trials of workplace effectiveness including economic evaluations are still needed to identify the potential long-term costs and benefits in terms of musculoskeletal disorders, work productivity, and potential predictors of workplace success.
- If found to be useful and economical, implementation efforts will need to address the social and cultural context in the locality where implementation is planned.
- This study had a relatively small sample for inferential tests investigating quantitative differences between working with and without the exoskeleton, and it also may have selection bias which could make it unrepresentative of Canadian farmers. Larger sample sizes, in terms of participants, tasks, and geography, can help determine whether the results from this small sample hold true in a larger more representative population sample; this would allow for stronger confidence in the research outcomes.

## Conclusion

After assessing the impact of the exoskeleton with 6 lab participants and 15 farm participants from 12 farms, we conclude that there is potential for a back-supporting exoskeleton to help reduce physical load on farms. However, the degree of success will depend on an appropriate match between the exoskeleton, the farmer, and the task. Exoskeletons need to fit the worker, and time needs to be taken to adequately adjust and customize a device, especially for those who are outside the central range of body dimensions. Note that the additional weight of the exoskeleton may impact smaller people, and access to different models may be required.

In terms of a task match, it seems clear that there are some hazards in the farm environment that are not conducive to exoskeleton use, and there needs to be a robust solution to the risks introduced by catching the exoskeleton on machinery or equipment. The practicality of the exoskeleton in a multi-task work day would need to be navigated, particularly the potential for donning and doffing for machinery operation. At the same time, we saw reductions in muscle activity during very heavy manual tasks like ‘lifting bales’ and ‘lifting feedbags’, which may potentially enable farmers to better tolerate these heavy tasks as they age. This particularly applies to farmers who work alone on farms that are in isolated rural areas, where it may be difficult to find the ‘helping hand’ needed to share a heavy task; casual or temporary workers may not be available in rural areas. Although the heaviest tasks are not usually highly frequent, they are all the same intrinsic to a successful farm operation. Ultimately, a farmer’s limited capability to perform these tasks could limit a farm’s productivity this could influence a farmer to choose retirement even when they are still capable of most other tasks. The same could apply to women farmers, who are growing as a proportion of the farm workforce and who, on average, have a lower physical capacity than men. Reducing physical load for the most demanding tasks could potentially extend farmers’ productive working life, particularly in remote areas with limited assistance. Although this study finds potential in exoskeletons, additional research is required before recommending their use on farms.

The findings from this research are intended to inform future technology development to realize improvements in farmers’ health and productivity. It is hope that the improved understanding of how an exoskeleton may contribute to better work posture and productivity will ultimately increase the economic sustainability in farm families in Alberta and beyond.

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