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The Potential for Exoskeletons to Improve Health and Safety in Agriculture—Perspectives from Service Providers

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OCCUPATIONAL APPLICATIONS The use of exoskeletons has the potential to benefit workers by supporting non-neutral work postures and reducing physical exertions. However, little is known about the specific factors that may influence the adoption and use of exoskeletons in the agricultural sector. We captured the perspectives of experts in Farm Health and Safety on the potential for exoskeleton use in farming. Lifting/carrying heavy loads, operating hand tools, and climbing equipment were highlighted as tasks most likely to benefit from exoskeleton adoption. Back and knee exoskeletons were ranked as the modules with the greatest potential for application. Affordability, durability, compatibility with farming equipment, and versatility when operating diverse kinds of machinery emerged as the most important adoption factors. Body stress, getting caught on equipment, unexpected failure and fall risks were highlighted as key barriers to adoption. These results are discussed to enable the agricultural sector to benefit from exoskeleton technologies in practice.

KEYWORDS Assistive technology, farming, ergonomics, technology adoption

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INTRODUCTION

Musculoskeletal Disorders (MSD) are more prevalent in farmers than non-farmers, with the low back being the most common body region of the reported problems (Fathallah, 2010). A recent study of agricultural workers in the US Midwest showed farmers to have double the risk of back pain compared to the general working population, and that farmers were eight times more likely to make a significant change in their work activities due to back pain (Fethke, Merlino, Gerr, Schall, & Branch, 2015). In addition to high rates of back pain, other work-related injuries and joint diseases such as arthritis also frequently cause mobility impairments among aging farmers, thus affecting their ability to perform their work safely and effectively (Browning, Truszczynska, Reed, & McKnight, 1998; Mac Crawford et al., 1998; Sprince et al., 2003). Furthermore, farmers may also encounter limitations to appropriate care due to their rural location.

Agricultural tasks frequently present ergonomic risk factors for MSD (Davis & Kotowski, 2007; Meyers et al., 2002), particularly heavy exertions and sustained or repetitive non-neutral postures. Engineering controls that modify the tools or environment, personal protective equipment, and/or training are some of the options for reducing the high rates of MSD in this population, as a change in work environment to reduce exposure to ergonomic risk factors may not always be practical. For instance, when prolonged stooped/squat postures are considered in the context of physical loading of the back and lower limbs, there is evidence that prolonged back bending can contribute to the prevalence of back pain (Hoogendoorn et al., 2000; Punnett, Fine, Keyserling, Herrin, & Chaffin, 1991), just as large cumulative exposures to deep knee flexion during squatting is related to an increased risk of MSD in the lower limbs, particularly the knees (Fathallah, 2010). However, tasks undertaken at ground level, such as calving or repairing fences, cannot be easily modified, since the ground height cannot be raised. Thus, alternative approaches are required to mitigate ergonomic risk exposures in agricultural work settings, and one potential intervention strategy is to wear a supportive structure or an exoskeleton.

An exoskeleton is a wearable device used to support and assist the strength and mobility of the wearer. Exoskeletons are rigid devices with linkage structures (mirroring the body joints) that either assist the wearer by producing torques that are a result of the user's motions (passive) or using powered actuators (active). Most often, the implementation of passive devices (for which the market is relatively more mature) is based on incorporating a non-adaptive, passive, spring-based system that either offloads the wearer when they hold a certain posture or absorbs and returns energy during alternating motions. This technology clearly has the potential to support extreme work postures and limit physical exertions, to thus reduce associated MSD risks. Although exoskeletons are currently used to reduce musculoskeletal exposures among assembly line workers in the workplace, for example in the manufacturing sector, the number of peer-reviewed studies on the industrial use of exoskeletons is limited, with most taking a perspective on mechatronics, not ergonomics. To our knowledge, most investigations of the ergonomic impacts of exoskeleton use have been controlled laboratory studies. For example, existing studies have demonstrated the efficacy of passive arm- or back-support exoskeletons during simulated occupational tasks (Abdoli-E, Agnew, & Stevenson, 2006; Bosch, van Eck, Knitel, & de Looze, 2016; Kim et al., 2018; Rashedi, Kim, Nussbaum, & Agnew, 2014; Spada, Ghibaudo, Gilotta, Gastaldi, & Cavatorta, 2017; Ulrey & Fathallah, 2013a, 2013b), finding reduced muscle activity, increased endurance time, and/or improved work performance.

Despite the positive outcomes found in such lab studies, there is limited evidence from the field: the development of exoskeleton technology is still in its infancy, and it remains unknown whether exoskeletons are suitable for reducing exposures related to MSD in agriculture, and what specific design characteristics may make exoskeletons more suitable for actual adoption among agricultural workers. This manuscript presents relevant stakeholders' perceptions about the potential for exoskeleton use in agriculture, factors likely to determine exoskeleton adoption among agricultural workers, and anticipated health and safety concerns for exoskeleton use. Through sharing these perspectives, we hope to facilitate future research efforts in exoskeleton development and adoption in the agriculture sector.

METHODS

We solicited responses from agricultural service-providers, with expertise in Health and Safety and Farm Rehabilitation Services, to obtain their opinions and concerns regarding exoskeleton technology in agriculture, with a focus on farmers with mobility impairments. A survey was used as the data collection instrument, which included closed- and open-ended questions and required about 25 min to complete (the survey is included in online supplemental material). The questions focused on common pain-inducing activities on the farm, the tasks that might benefit from the use of exoskeletons, the likelihood of use of different exoskeleton modules, the factors that may contribute to adoption or rejection of assistive technology, and potential health and safety risks of exoskeletons. The study protocol was approved by the Institutional Review Board at Virginia Tech. Participation in the survey was voluntary, and completion of the survey constituted informed consent.

The survey was distributed to a total of ~110 experts at the 2018 AgrAbility National Training Workshop (http://www.agrability.org/agrability-national-training-workshop/) and via email listservs to the AgrAbility professional community. A total of 18 complete responses was received, resulting in a response rate of ~16%. A precise response rate could not be computed, however, since the exact number of active emails and currently active AgrAbility members was unknown. The respondents had experience assisting small-to-medium scale farmers who engaged in physical labor on their own farms. Survey respondents were located in the states of Virginia ($n = 8$), North Carolina ($n = 3$), Illinois ($n = 1$), Missouri ($n = 1$), Ohio ($n = 1$), Indiana ($n = 1$), Tennessee ($n = 1$), New Mexico ($n = 1$), and Maine ($n = 1$). Among those who reported their job experience ($n = 15$), mean work experience in the agriculture sector was 11.8 years (SD = 8.8 years).

For the closed-ended questions in the survey, summary statistics were computed. Specifically, the prevalence rates of common physical impairments in the agriculture sector were ranked according to frequency. Next, respondents were asked to rate how frequently some physical movements (common to farming tasks) caused physical pain or discomfort to farmers. An open-ended question was asked about candidate physical movements on farms that would benefit from exoskeleton-use, along with concrete examples of specific tasks involving those movements. To understand which body-parts would be in the greatest need of exoskeleton assistance in agricultural activities, respondents were asked to rate how often different exoskeleton "modules" would be needed/used on a farm.

Other open-ended questions were designed to elicit stake-holder and expert perceptions of exoskeletons in farming and their potential adoption factors, as well as perceived health and safety risks. Since respondents may not have had first-hand experience with exoskeletons, they were asked to draw upon their experiences with traditional assistive technology, when appropriate. Responses to the open-ended questions were analyzed using content analysis (Forman & Damschroder, 2007). An inductive process was first used to obtain low-level codes, and similar codes from multiple questions were then combined into overarching categories/clusters. Inter-rater reliability was verified for the low-level codes by two of the authors (SU and RF), and the final themes were developed using an iterative approach by a single author (SU).

RESULTS

Five impairments—namely, back injury/pain, limb injury/pain, arthritis, weakness in the limbs, and weakness in the back—were stated as being most "frequently" prevalent among agricultural workers, by more than 70% of respondents (Fig. 1).The three most frequent pain-inducing physical movements identified by respondents were lifting and carrying loads, climbing

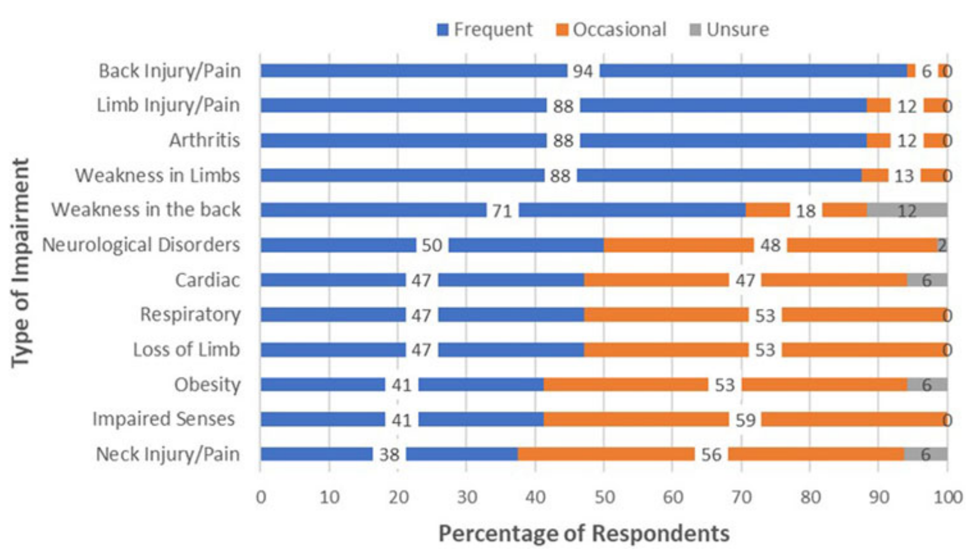

FIGURE 1 **Common physical impairments affecting agricultural workers, as indicated by survey respondents and ranked according to prevalence frequency.**

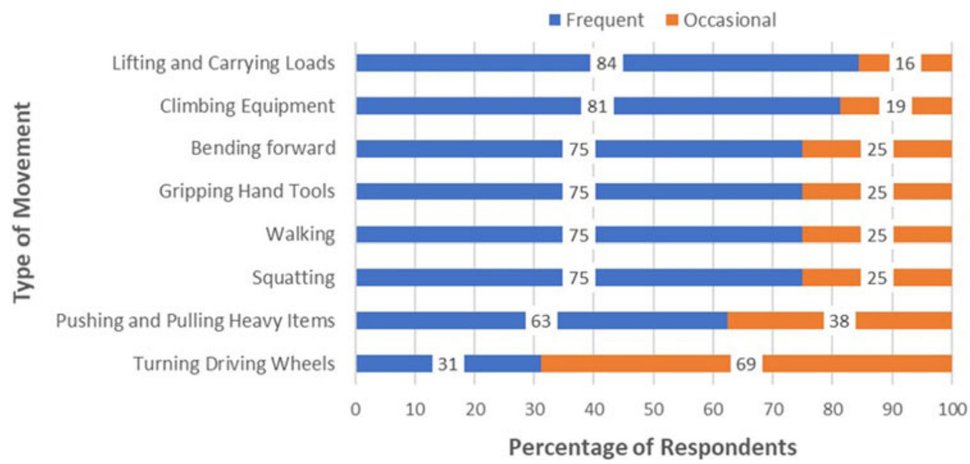

FIGURE 2 **Common pain-inducing movements in the agriculture sector, as indicated by survey respondents and ranked according to prevalence frequency.**

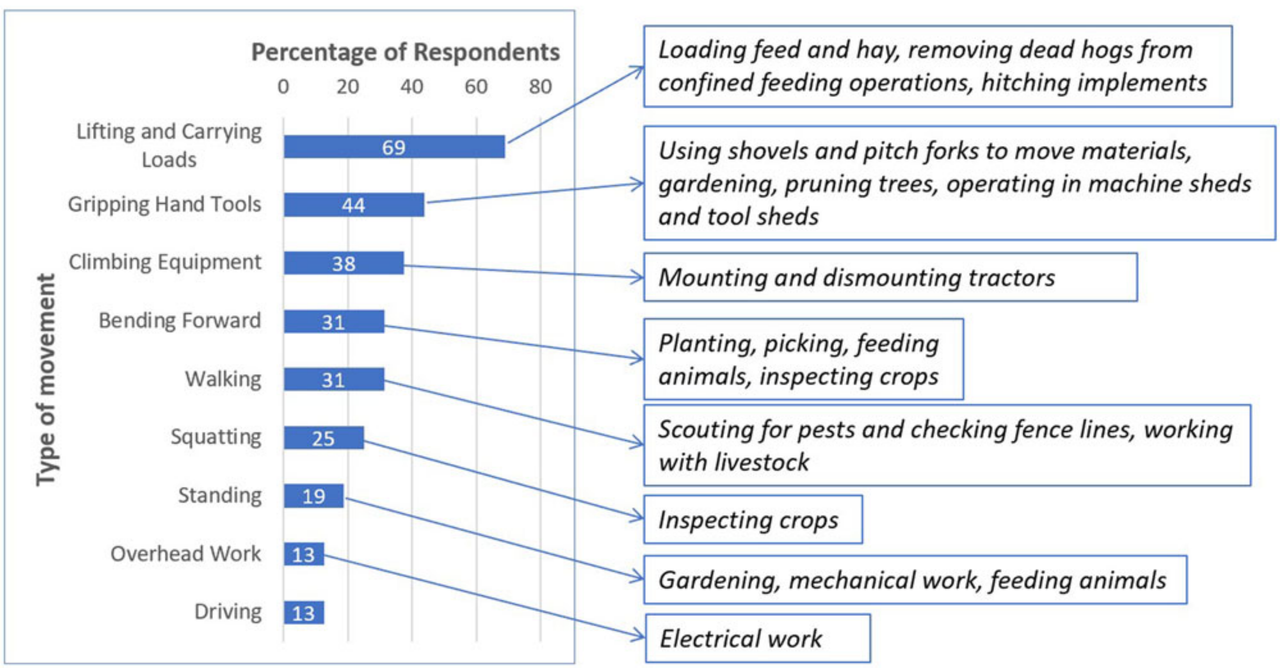

FIGURE 3 **Candidate movements for exoskeleton use (Left), ranked according to percentage of respondents listing each movement. Examples of specific tasks mentioned by the respondents are shown on the right.**

equipment, and bent/stooped labor (Fig. 2). The top candidate movements that could benefit from using exoskeletons, as identified by respondents, were similar to the top pain-inducing activities (Fig. 3). The top three exoskeleton modules that would be used frequently on farms, as identified by the respondents, were the back, knee, and hand modules (Fig. 4).

Exoskeleton adoption factors

The adoption factors that emerged from a content analysis of the open-ended responses are illustrated in Fig. 5. Service providers suggested that an ideal assistive device would be simple, practical, affordable, usable, and easy to maintain. Respondents said, *"it has to be a slimline design, and not cumbersome"*, and that it should be *"possible to wear under or over clothes."* An exoskeleton would need to exhibit *"flexibility of use while either standing, walking or sitting"*, especially since farmers need to drive tractors and combines in addition to doing physical work on the farm. It is also desirable to have *"minimal change to existing routine/method of work"*, and for the assistive technology to not hinder other farming operations or interfere with

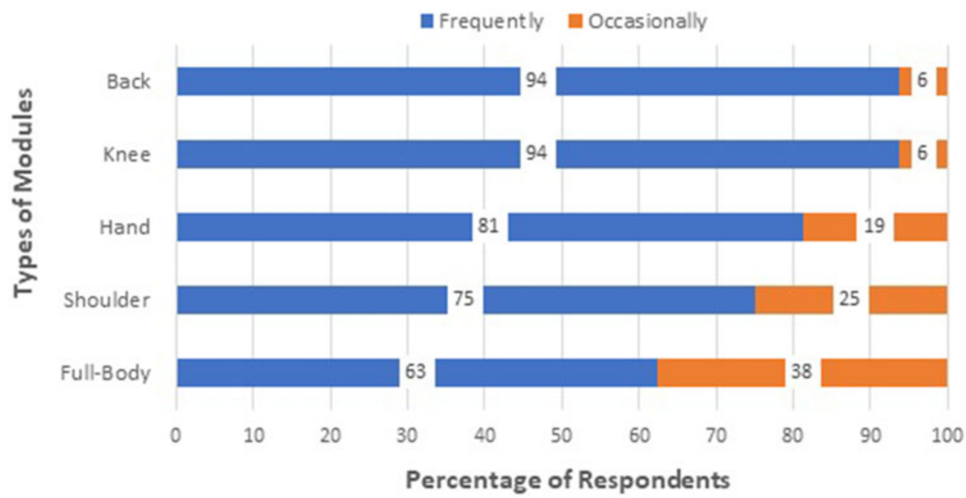

FIGURE 4 **Likelihood of use of exoskeleton modules, ranked according to prevalence frequency.**

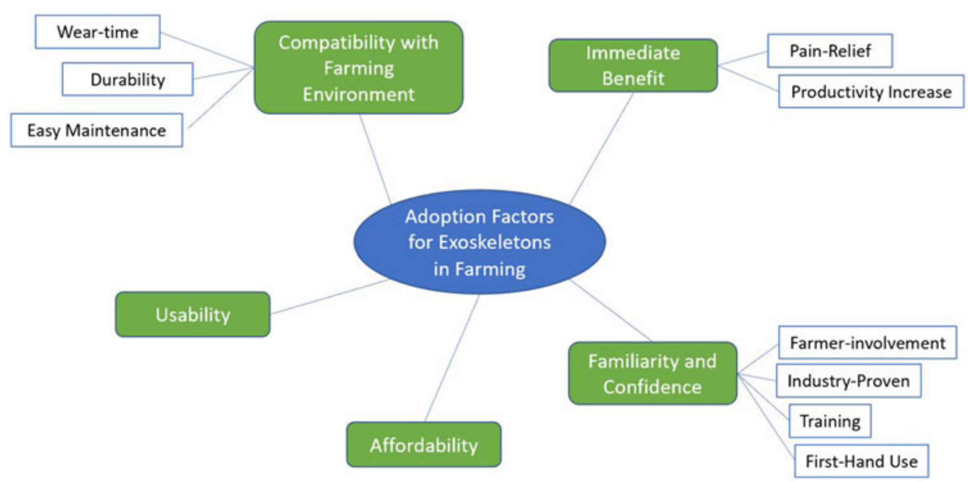

FIGURE 5 **Important adoption factors for exoskeletons, as mentioned by respondents in open-ended survey responses.**

equipment. The need for an easy-to-maintain exoskeleton was best illustrated by the following statement: *"If the technology has to be sent a considerable distance for repair or maintenance and is away from the worksite more than a few weeks, it could lead to technology abandonment."*

For an exoskeleton to be successfully adopted, respondents agreed that it would have to be compatible with the farming environment and its harsh and time-intensive nature. The device would have to work well in *"closed environments (e.g., grain bins, ladders, etc.)."* It would also have to be durable, and any inability of the exoskeleton *"to survive the dirt, water, and corrosive conditions of the farm"* would be a significant barrier. One respondent said, *"The time to put on/take off the exoskeleton will be critical, or in the alternative, the ability to wear the device for all purpose uses."* In the case of an active exoskeleton, charging time and limited battery capacity could also contribute to time delays. For instance, a respondent shared: *"If it is motorized with battery, how long does it take to charge? How long does the charge last?"*

A significant, immediate benefit in terms of both pain reduction and enhanced productivity was noted as a strong promoter for any assistive device, including an exoskeleton. *"Decreases pain/exertion"*, and *"gets job done faster and safer"* were the main desired benefits. Regarding exoskeletons specifically, one respondent said, *"Farmers will use what gives them a competitive edge, and if an exoskeleton reduces fatigue and enables performing tasks with less pain, effort, and is capable of performing maximal lifts… it will demonstrate its value."* Respondents said that farmers are likely to discontinue the use of assistive devices that do not seem to be work-related, and that are more "medical" in their appearance

FIGURE 6 **Important Safety/Health Risks of exoskeletons, as mentioned by respondents in open-ended survey responses.**

and function. Farmers can feel *"self-judgment centered on not wanting to be dependent on a non-farm related contraption."* One respondent believed that an exoskeleton would be more valued if "*it doesn't look 'medical' but looks like a 'smart' industrial use device.*" The comments about competitiveness, self-judgment, and the look-and-feel of the exoskeleton suggested that cultural phenomena and attitudes in agriculture may influence the adoption of exoskeletons.

Some respondents suggested that helping farmers achieve familiarity with, and confidence in an assistive technology, would facilitate the adoption process. Training was the most frequently mentioned factor in this category. For instance, a respondent shared: *"Demonstrating how the devices work, how to adjust them, how to best use them helps ensure good results."* Specifically, hands-on training and rote practice were emphasized, because this would improve understanding of the limitations and strengths of the technology: *"If they see how it can benefit them, they instantly use the device*" and *"they will need to try the device on the farm.*" Farmers seemed to want to be directly involved in the design and selection of assistive technology; as one respondent said, *"Most of the accommodations we provide are specifically requested by the client. They often know exactly what they need. They just need help making or obtaining those devices."* For these respondents, farmers are more likely to adopt a device that is a *"commercially available product from a known agricultural supplier,"* and they would be receptive to *"marketing campaigns with real farmers using the product."*

A notable finding is that although four respondents mentioned religion, tradition, peer judgment, and ridicule as barriers to adoption, there were also three other respondents who said that such psychosocial factors would be *"outweighed by benefits"* and that they *"can be overcome with time."* These numbers are intended to highlight a potential difference in perspectives among service providers and may not exactly represent the population of farmers. Although psychosocial factors are acknowledged to have a potential impact, it may be that device effectiveness, training, or other factors play a larger role in adoption. Further investigation may be needed to establish the relative importance or "weight" of psychosocial versus other factors in terms of how they may influence exoskeleton adoption.

Potential safety/health risks

Potential health and safety risks to exoskeleton adoption that emerged from a content analysis of the open-ended responses are illustrated in Fig. 6. Stress on the body due to poor design was specifically mentioned by ~77% of respondents as a potential risk. *"Getting hurt while putting on the exoskeleton," "discomfort and possible skin irritations,"* the lack of breathability, *"heat build-up"*, and *"rubbing or chafing on a bony prominence*" were mentioned as potential barriers. The weight of the exoskeleton itself was brought up as a possible stress-inducing factor, as well as *"postural adaptations to accommodate the device that result in a secondary musculoskeletal disorder."*

Respondents (~30%) were concerned about falling as a risk, especially if the exoskeleton is heavy and cumbersome. One person specifically brought up the issue of *"how to get up if one falls"* and another mentioned about the possibility of *"injury from falling with the device on (e.g., falling onto hard/bulky projections)."* Approximately 69% of respondents suggested that the exoskeleton could get caught in equipment and potentially cause injury. Specific examples given by respondents were *"getting caught in PTO (power take-off) or belt and chain drives," "hang up in forage, tree limbs and other debris,"* or misjudging the distance between oneself and farming equipment.

Close to half of respondents raised the concern of an unexpected failure of the exoskeleton. Some mentioned specifically *"unexpected power failure of powered exoskeleton,"* and stressed the importance of having *"the ability to deactivate it"* if such an event occurs. It was noted to be especially risky if the exoskeleton were to fail *"during a critical movement (e.g., climbing)."* It is worth mentioning that these comments referred largely to an 'actively powered' exoskeleton, versus a passive one.

Thus, design features such as appropriate indicators and warnings on the exoskeleton interface may be needed to alleviate concerns such as 'range anxiety', as well as failure mode effects analyses that focus on unexpected loss of control and necessary countermeasures.

Lastly, 15% of respondents were concerned about the risks of overuse by farmers who *"think they aren't causing damage to themselves while wearing the device."* There is a possibility that farmers might *"attempt more difficult tasks/climbs"* which would expose them to a heightened risk of injury.

DISCUSSION

According to the respondents to our survey, to support potential adoption exoskeletons in farming are expected to provide an immediate, perceptible benefit to farmers, be affordable, and suitable for the farming environment. Exoskeletons may, in fact, have even more impact in the agricultural sector compared to other industrial sectors, because of the dynamic nature of farm work that limits the use of other intervention strategies requiring extensive modification to the work environment. Usable and farm-friendly exoskeletons may also allow farmers with mild to moderate mobility impairments to work, without having to make extensive modifications to their work tools, such as adding lifts to tractors or buying specialized hand tools.

Unlike in the manufacturing industry, where most purchasing decisions are made by upper management and not end-users, the agricultural sector involves farmers who often make buying decision themselves. It will thus be important to design and market exoskeletons accordingly. Our results (Figs. 3 and 4) suggest that certain body parts may have a greater need for exoskeleton assistance than others. The specific task examples provided by respondents (Fig. 3) may also be useful to researchers hoping to design laboratory tasks that representative of farming tasks. Affordable prices and a widespread service-center network that provides accessible maintenance and repair seem vital. These can be achieved through promoting manufacturer awareness regarding opportunities and specific needs in agriculture, and by introducing healthcare policy that improves the overall accessibility of exoskeletons to farmers.

Some limitations of the current study are that, as an exploratory effort, our sample size was limited both in size and in geographical area, and most study respondents were familiar with small-to-mid sized farm operations primarily involving farmers who provide labor on their own farms. Hence our findings may be not be generalizable to all types of agriculture or agricultural workers. Further research using larger sample sizes, on diverse farm types and their specific task demands, may reveal concrete needs and preferences for certain types of exoskeletons over others.

In conclusion, recent advancements in exoskeleton technologies offer new approaches with the potential to enhance performance and reduce MSD risks in agriculture. Lifting and carrying heavy loads, operating hand tools, and climbing equipment were highlighted as candidate tasks that were most likely to benefit from exoskeleton adoption. In addition to being effective, results from the survey emphasized the need for exoskeleton designs to be simple, affordable, usable and durable, compatible with farming equipment, and versatile when operating diverse kinds of machinery and performing dynamic tasks, in order to be adopted in the agricultural sector. Finally, agriculture has a unique cultural context and farmers take considerable pride in their work (Ahnström et al., 2009; Willock et al., 2008). Exoskeleton designs that are aligned with the cultural context of agriculture and that exude a sense of empowerment may facilitate greater levels of adoption.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

SUPPLEMENTAL MATERIAL

Supplemental data [material/appendices] for this article can be accessed on the publisher's website at http//10.1080/24725838.2019.1575930.

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