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# Forestry professionals' perspectives on exoskeletons (wearable assistive technology) to improve worker safety and health

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**ABSTRACT**

Exoskeletons have been recognized as an effective ergonomic control to reduce physical risk factors, including forceful exertions and awkward postures that are common in manual timber felling. However, no evidence exists to date that offers industry perspectives, important facilitators, and potential barriers for adopting exoskeletons in the forest industry. Therefore, this study aimed to quantify biomechanical stress of timber fellers and assess forestry professionals' awareness and acceptance of exoskeletons. We measured working postures using wearable sensors during manual timber felling [*N* = 10] to suggest appropriate and beneficial exoskeleton types for timber fellers. We examined forestry professionals' awareness and acceptance of exoskeletons and identified perceived barriers and risks using a questionnaire [*N* = 22]. This study revealed that the forestry professionals expressed considerable interest and acceptance level in exoskeleton use. The important factors influencing the adoption of exoskeletons identified in this study were weight, comfort, simplicity/portability, practicality (usable and easy to use), and easy maintenance. The results also identified timber felling, cutting/sawing, and mechanic work as potential forestry tasks that may benefit most from the exoskeleton use. The wearable sensor data showed that manual timber felling posed substantial torso bending and upper-arm elevation. Given the awkward posture and high prevalence of musculoskeletal pain in the back and upper-arms, this study suggests that back-support and upper-limb support exoskeletons may be suitable to the forest industry. This study provides important insights for future studies investigating the feasibility, readiness, and effectiveness of exoskeletons to be applied to the forest industry.

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**KEYWORDS**
Manual timber felling; musculoskeletal disorders; posture; inertial measurement unit

## Introduction

Logging is an important industry in many countries around the world. In the United States, logging provides approximately 25,000 jobs across the nation as an important source of employment in many rural communities (U.S. Bureau of Labor Statistics, BLS 2021). Despite its significant economic footprint, logging has been one of the most dangerous jobs in the United States with the highest fatality and injury rates (U.S. Bureau of Labor Statistics 1992-2016, 2017; Janocha and Hopler 2018). The fatality rate of forestry workers is 20–30 times higher than the average of all other industries (Sygnatur 1998; Shaffer and Milburn 1999; Janocha and Hopler 2018), and their non-fatal injury rate is 40% higher compared to the all other industry average (Janocha and Hopler 2018). When considering both non-fatal and fatal injuries, forestry has the highest injury cost per worker, over 18 times higher than those in the lowest risk job categories (Leigh et al. 2006).

Previous studies have shown that many fatal and non-fatal injuries are highly associated with manual timber felling with a chain saw and associated in-woods operations, such as delimbing and bucking trees (Gallis 2006; Albizu-Urionabarrenetxea et al. 2013). Such highly prevalent injuries can be attributed to the physically demanding nature of the work that is performed in rugged terrain, often under adverse weather conditions with unstable footing. Timber harvesting has become more mechanized in many places, reducing the injury risks during timber felling by replacing people on the ground with machines (Axelsson and Pontén 1990; Bayne and Parker 2012; Bonauto et al. 2019; Garland et al. 2019). However, such mechanization may not completely remove manual timber felling, especially in steep rugged terrain inaccessible to harvesting machinery (Pokharel et al. 2023).

The manual timber felling tasks pose various physical risk factors including forceful exertions, awkward postures, repetitive motions, and hand-arm vibration, which have long been associated with work-related musculoskeletal disorders (MSDs) (Chaffin et al. 1999; Gallis 2006). Previous epidemiological studies have shown high prevalence (over 70%) of MSDs among the forestry workers with low back and shoulder being most affected areas (Sairanen et al. 1981; Axelsson and Pontén 1990; Harstela 1990; Gallis 2006; Lynch et al. 2014). These physical risk factors could potentially increase muscular fatigue resulting in increased risks of fall (Davidson et al. 2004, 2009; Pline et al. 2006; Wilson et al. 2006; Lin et al. 2009; Larson and Brown 2018), which is another major source of injuries in the logging process (Quandt et al. 2013). Despite the extensive research that has been conducted on preventing fatalities in forestry work, there remains a significant gap in

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the literature when it comes to exploring non-fatal injuries, particularly musculoskeletal disorders, in this profession. Therefore, it is essential to assess the risks associated with non-fatal injuries and develop effective prevention measures to protect forestry workers.

Exoskeletons (Figure 1) have recently been developed to provide postural support or enhance workers' capabilities with a continuous power input (active) or without any power (passive) (Schnieders and Stone 2017; Weston et al. 2018). This emerging technology is gaining attention as a promising ergonomic control to reduce physical risk factors in several industries including shipbuilding, automotive, and aerospace manufacturing (Junpei et al. 2008; Sylla et al. 2014; Bosch et al. 2016; de Looze MP et al. 2016; Schnieders and Stone 2017; Weston et al. 2018). Previous studies showed that exoskeletons reduced the biomechanical loading in the shoulders (Junpei et al. 2008; Sylla et al. 2014; Van Engelhoven et al. 2018) and low back (Kim et al. 2018) during overhead work while improving work performance (Kim et al. 2018). In contrast, other studies showed that exoskeleton use may have limited benefits (Weston et al. 2018; Picchiotti et al. 2019) and introduce potential health hazards including reduced postural balance (Schiffman et al. 2008; Spada et al. 2017), increased muscular demand in antagonist muscles (Rashedi et al. 2014; Theurel et al. 2018), reduced range of motion (Kim et al. 2018), and transferred load to other body parts (Rashedi et al. 2014; Theurel et al. 2018; Weston et al. 2018). These limitations may pose important safety hazards especially in the case of an emergency during timber felling (e.g. workers' reduced mobility and delayed evacuation).

Figure 1. Passive exoskeletons: (a) upper-limb and (b) low back exoskeleton.

Despite the growing body of research, these potential benefits and risks of exoskeleton use may not provide direct implications to manual timber felling for the unique nature of the forestry work described in previous studies (e.g. non-standardized work, forceful exertion, awkward postures, long shifts, fast-pace) (Kirk and Sullman 2001; Lilley et al. 2002) and physical environment (e.g. climate, terrain, remote work location) (Slappendel et al. 1993). In current literature, there is a lack of research pertaining to the feasibility, potential benefits, and risks of exoskeleton use in forestry settings. Successful adoption of new technology normally requires a clear understanding of both benefits and risks, as well as willingness, perseverance and behavior change on the part of the adopter. As the preliminary step prior to field applications of exoskeletons in forestry as a potential intervention for reduction of MSDs, this study aimed to objectively quantify biomechanical stress of timber fellers and assess forestry professionals' awareness and acceptance of exoskeletons. The findings of this study identified several factors that could help improve the adoption and acceptance of exoskeletons, as well as potential forestry tasks that could benefit from their implementation. Perceived barriers and risks to exoskeleton use in forestry were also identified. These results are crucial for guiding the development and implementation of exoskeletons as a potential ergonomic control to reduce biomechanical stresses and associated injury risks among forestry workers.

## Materials and methods

This study consisted of two parts:

(1) A field-based sensor study [$N = 10$] to characterize biomechanical stress during manual timber felling using wearable inertial measurement unit (IMU) sensors (Kim and others 2022)
(2) A survey study [$N = 22$] to collect forestry workers' awareness of exoskeletons and identify important technology adoption factors, potential forestry tasks for exoskeleton use, exoskeleton characteristics for improving workers' acceptance of exoskeleton, and perceived barriers and risks to implementation of exoskeletons in forestry.

### *Participants*

Participants for the field and survey studies were recruited as a convenience sample through the support from local forest industry partners, the Pacific Northwest Agriculture Safety and Health (PNASH), and USDA Forest Service District Offices in Oregon and Idaho. All the study protocols were approved by the University's Institutional Review Board and all the participants provided signed consent prior to data collection.

For the field-based sensor study, a total of 10 professional timber fellers (9 males and 1 female) participated in the field-based sensor study. Eligibility criteria included at least 21 years of age and currently working as professional timber fellers.

For the survey study, an online questionnaire was distributed via our forest industry partners, colleagues in academia,

**Table 1.** Participant demographics [$N = 22$].

| Demographics | Mean (SD) |
|---|---|
| Age (years) | 40.1 (13.3) |
| Working experience in forest industry (years) | 20.7 (14.3) |
| Gender | Count |
| Male | 21 |
| Female | 1 |
| Job title* | Count |
| Timber feller | 10 |
| Cable logger | 4 |
| Equipment operator | 8 |
| Trainer | 2 |
| Safety Officer | 6 |
| Other (manager, CEO, etc.) | 8 |

*Participants held multiple job titles (22 participants held 38 job titles).

and PNASH to solicit responses from forest industry stakeholders. Eligibility criteria included at least 21 years of age and professional forestry workers knowledgeable and experienced in manual timber felling. We also administered the paper-based survey to the 10 field-based sensor study participants in person. A total of 22 forestry stakeholders (21 males and 1 female) in four different states, Idaho ($n = 5$), Montana ($n = 1$), Oregon ($n = 15$), and Washington ($n = 1$) responded. Most of the participants were directly involved in timber felling activities. As many of them worked in different jobs in forestry, some participants reported multiple job titles (i.e. 38 job titles among 21 participants): timber fellers (26%), cable logging crew (11%), and equipment operators (21%). Other job titles included trainer (5%), safety officers (16%), and managers/CEOs (21%). The response rate is not available because the number of forestry workers who received the questionnaire was not available. Their demographic information is summarized in Table 1.

### *Inertial measurement unit (IMU) sensor data collection and analysis*

This IMU sensor-based approach has been validated and used to measure torso and arm postures during outdoor occupational work including apple harvesting (Thamsuwan et al. 2019) or commercial fishing (Kim et al. 2022) tasks in the field settings. Inertial measurement unit (IMU) wireless sensors (Biostamp nPoint; MC10; Lexington, MA) were used to collect participant's body postures (torso and shoulder) during their regular work shift. As all the participants ($N = 10$) were right-handed, they operated their chainsaws by holding the front handle with the left hand and the trigger with the right hand (Figure 1). The accelerometers in the IMU sensors were set at a range of ±8 g with precision of 0.6 milli-g and a sampling frequency of 62.4 Hz (Kim et al. 2022). Before beginning the participant's daily work shift, three IMU sensors were placed on the torso (the midpoint of sternum) and the lateral aspects of the left and right arms directly below the middle deltoid muscle (one-third of distance from acromion to the lateral epicondyle) (Kim et al. 2022).

After the sensors were placed, the participants performed standardized postures (T-pose for 3 seconds, three torso flexions, and five arm abductions) to check the sensor placement and orientation (Thamsuwan et al. 2019; Kim et al. 2022). During their work, the IMU sensors continuously collected raw acceleration data. As each of the three sensors had an internal clock, all the three sensors were able to continuously synchronize via Bluetooth and save the data in its self-contained memory. When their first work shift (3–4.5 hours) was completed, the sensors were retrieved, and the raw acceleration data were saved into a cloud server.

The raw acceleration data were filtered using a dual-pass 1-Hz low-pass Butterworth filter (Kim et al. 2022). The filtered acceleration data were used to calculate arm elevation ($\theta_{Arm}$) and torso flexion ($\theta_{torso}$) angles (Figure 2) as shown in Equations 1 and 2 (Thamsuwan et al. 2019; Kim et al. 2022):

$$\theta_{arm} = \tan^{-1}\left(\frac{\sqrt{x^2 + y^2}}{z}\right) \quad (1)$$

$$\theta_{torso} = \tan^{-1}\left(\frac{x}{z}\right) \quad (2)$$

*where*, $x$(forward), $y$(lateral), *and* $z$(vertical) *are acceleration on the* $X/Y/Z$ *axes.*

The posture angles were summarized as the 5th, 50th, and 95th percentile (Johnson et al. 2002; Thamsuwan et al. 2019; Kim

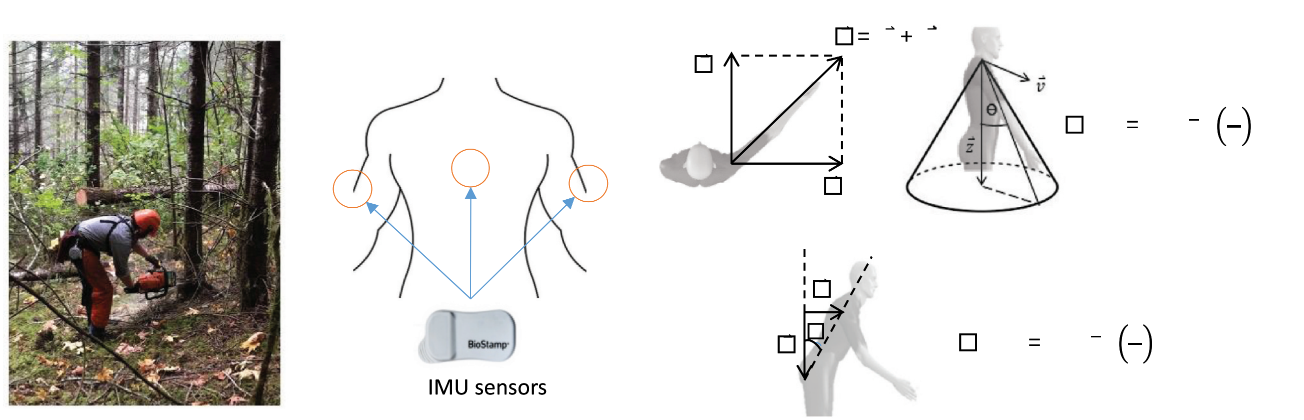


**Figure 2.** The placement of inertial measurement unit (IMU) wireless sensors modified from Kim et al. (2022). A picture showing manual timber felling (left); three IMU sensor placements on the torso and the arms (middle); a schematic view of torso ($\theta_{torso}$) and arm angle ($\theta_{arm}$) calculation based on tri-axial acceleration collected from the IMU sensors (right).

et al. 2022). Using the posture data, the percentage of work time that the workers spent on specific torso and arm postures (0–30, 30–60, 60–90, and greater than 90 degrees) during manual timber felling were calculated as shown in Equation 3:

$$\%\ Work\ Time_{Posture} = \frac{Duration_{Posture}(inseconds)}{Total\ Measurement\ Duration\ (inseconds)} \times 100 \quad (3)$$

$$where, Posture = \begin{cases} 0 - 30^\circ \\ 30 - 60^\circ \\ 60 - 90^\circ \\ > 90^\circ \end{cases}$$

### *Survey data collection and analysis*

The survey was developed by modifying and integrating previously validated interview forms and questionnaires (Sun et al. 2015, 2018; Upasani et al. 2019) that have been used to evaluate the adoption and usability of new technologies. These questions were designed to collect professional background and musculoskeletal pain; assess their awareness and opinions about exoskeletons; identify perceived barriers and risks associated with exoskeleton use in forestry settings; and identify and characterize tasks that can significantly benefit from exoskeletons. Prior to actual distribution, the developed questionnaire was shared with three manual timber fellers and ergonomics/safety supervisors at the partner logging companies for validation. The structure of the questionnaire was:

- Section 1: Professional background/demographic information (job title, state residency, age, gender, years of work experience) was collected. In addition, musculoskeletal pain in the past week (7 days) was collected for seven different body parts (neck, shoulders, low back, wrist/forearms, knees, legs, and ankles/feet) using a 10-point visual analog scale (Borg CR-10) with verbal anchors (0 = no pain to 10 = worst pain you can imagine) (Borg 1982).
- Section 2: Familiarity with issues in the forestry sector that pertain to logging safety and health was collected using a 5-point Likert scale (1 = not familiar at all; 5 = extremely familiar).
- Section 3: Among the technology adoption factors identified in a recent study (Upasani et al. 2019), the participants were asked to rate the importance of each factor (simple, practical, affordable, proper training, easy maintenance, after-sales support, and reduction in worker compensation rate): From the least important (1) to most important factor (5) that would help you or your coworkers adopt and get comfortable with using new assistive technology such as exoskeleton. The importance was determined by the product summation of the rate and its count (frequency). Hence, the range of the importance measure is from N (all respondents rate a factor as the least important factor = 1 × N) to 5N (all respondents rate a factor as the most important factor = 5 × N).
- Section 4: The participants were asked to provide potential tasks that may benefit most from the exoskeleton use as well as important characteristics for accepting exoskeletons. Each of the five important design characteristics (support, portability, weight, time to wear, comfort) was rated from the least important (1) to the most important (5). The importance of each factor was determined by the product summation of the rate and its count (frequency) as described earlier. In addition, we posed an open-ended question on other characteristics that might influence adoption of exoskeletons. Lastly, we solicited the responses on potential barriers (financial, productivity, psychosocial, physical, and other barriers) via an open-ended question. Examples of each barrier were provided to assist the participants: Financial barriers (e.g. device costs); productivity barriers (e.g. possible reduced productivity due to getting accustomed to exoskeleton devices or reduced movement); psychosocial barriers (e.g. lack of trust in the technology, fear of judgment from peers, slow to adopt new technology); physical barriers (e.g. incompatibility with traditional logging equipment, uncomfortable wearable devices, time to put on/take off).

For the demographics, visual analog scales, and closed-ended questions (Sections 1–4 in the survey), descriptive data analyses were performed. Briefly, the demographic information was summarized as the average, standard deviation (SD), and count. The musculoskeletal pain data were summarized as the average and SD. The pain prevalence was calculated by dichotomizing the pain data (i.e. people with or without pain). The pain score of 1 or greater was considered as the presence of pain. Then, the number of people with pain per body part divided by the number of all the participants. For the open-ended questions on other characteristics that might influence adoption of exoskeletons and potential barriers (i.e. financial, productivity, psychosocial, physical, and other barriers) in the survey (Section 4), the content analysis was used to summarize the results (Forman and Damschroder 2007; Upasani et al. 2019).

## Results

### *Biomechanical stress assessment using wearable sensors during manual timber felling*

The average measurement duration for the wearable sensor data was 3.9 hours (SD: 0.7), ranging from 3.1 to 4.6 hours. The results showed that the median ($50^{th}$ percentile) torso flexion was 23.3° ($5^{th}$–$95^{th}$ percentile: 7.0–45.4°) during the manual timber felling (Figure 3-a). The manual timber fellers spent more than 30% of their time with torso flexion greater than 30° (Figure 3-b). The median (50th percentile) upper-arm elevation angles in the right and left arm were 23.6 and 25.6°, respectively. The peak upper-arm elevation angles were up to 61.8° (Figure 3-a).

### *Musculoskeletal pain*

Musculoskeletal pain was collected in seven different body parts: neck, shoulders, low back, wrist/forearms, knees, legs, and ankles/feet. The pain data analysis was limited to the

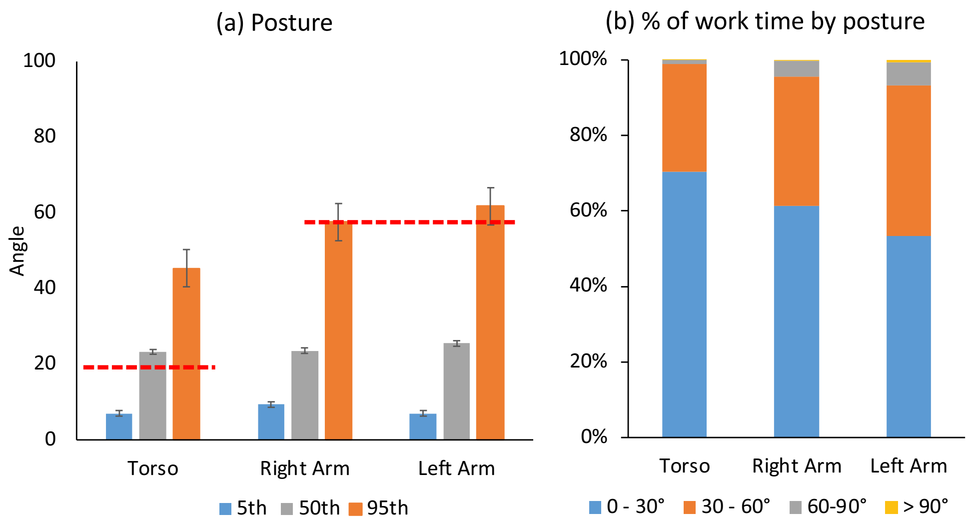


Figure 3. Mean and standard error of the 5th, 50th, and 95th percentile torso and upper-arm posture during manual timber felling ($N$ = 10). The red dotted line is a threshold value of torso flexion (20°) and arm elevation (shoulder flexion angle of 60°) indicating increased risks for back and shoulder injuries, respectively, when torso flexion and arm elevation angles are above the thresholds (Punnett et al. 1991; Keyserling et al. 1992; Bernard 1997).

forestry workers who performed timber felling tasks (13 of 21 participants) and summarized in Figure 4. Low back pain was the most prevalent musculoskeletal pain with the average pain level of 3.7 in the 10-point scale. Pain in the shoulders, wrist/forearm, and knees were also highly prevalent (85%) (Figure 4).

## Forestry workers' awareness of exoskeletons and other assistive technologies that pertain to logging safety and health

About 90% of the participants reported being either extremely or very familiar with logging-related tasks. However, the majority (~53%) of the participants said that they were not familiar with assistive technologies such as exoskeletons at all and 21% said that they were slightly familiar. Overall, around 74% of the participants were not very familiar (i.e. not familiar at all or slightly familiar) with assistive technologies available.

## Technology adoption factors

The importance of the adoption factors was determined by the product summation of the rate (range: 1–5) and its count (frequency) based on the collected data. As 20 participants completely responded to this question, the range of the importance in each factor ranged from 20 (all 20 respondents rated a factor as 1 – the least important factor) to 100 (all 20 respondents rated a factor as 5 – the most important factor). The importance score (20–100) for adoption showed that practicality, simplicity, and easy maintenance were the most important factors influencing the adoption of exoskeletons (Figure 5). After-sales support, proper training, and affordability were also considered as important factors in adoptions.

## Potential tasks for exoskeletons

The participants also identified potential tasks for exoskeleton application in the timber harvesting industry. Timber felling

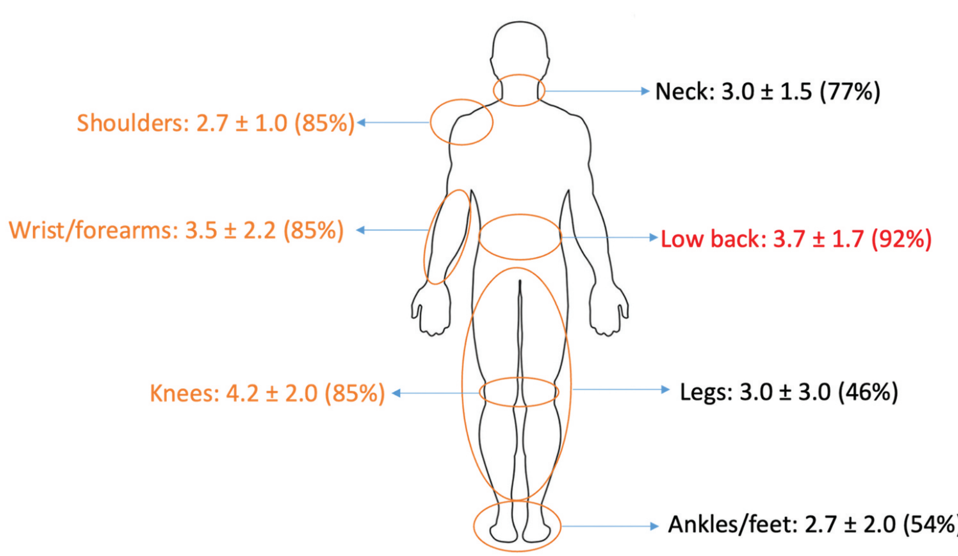


Figure 4. Mean (± standard deviation) musculoskeletal pain and its prevalence (%) by body part among forestry workers who performed timber felling ($N$ =13). The prevalence (%) was the number of people with pain each body part divided by the number of forestry workers (i.e. timber fellers).

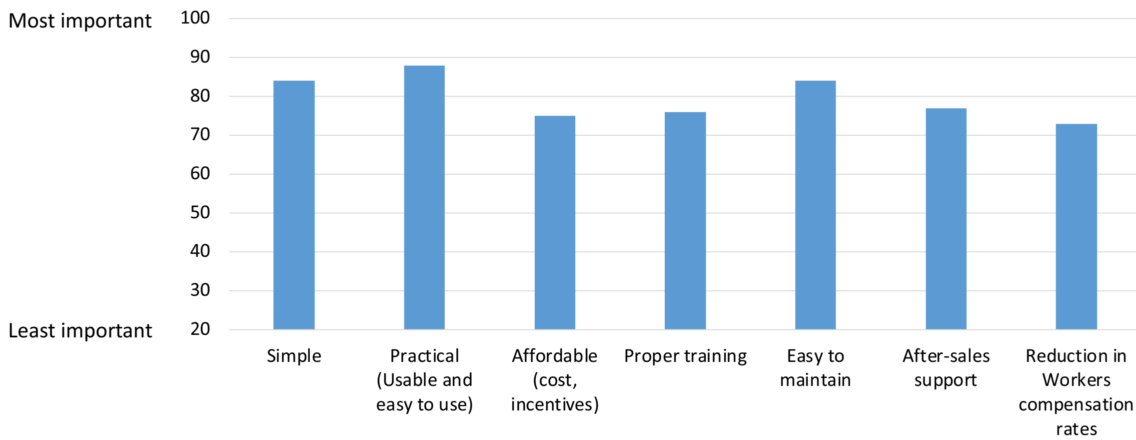


**Figure 5.** Importance of adoption factors (*N*=20). The important score was determined by the product summation of the rate ranging from 1 (the least important) to 5 (the most important) and its count (frequency). With 20 respondents in this study, the importance score ranged from 20 (all 20 respondents rate a factor as the least important factor = 1 x 20) to 100 (all 20 respondents rate a factor as the most important factor = 5 x 20).

and mechanic work were standing-out candidate tasks that may benefit most from using exoskeletons (Figure 6). Timber felling includes activities involving delimbing, bucking, and felling trees with a chain saw. About one-fourth of the respondents identified bending/lifting and carrying tasks for potential exoskeleton applications. Bending/lifting and carrying tasks are associated with manual material handling (e.g. lifting and carrying heavy objects such as logs and branches).

### Exoskeleton characteristics and health risks for accepting exoskeletons

Important exoskeleton design factors for greater acceptance were weight and comfort (Figure 7). The participants also valued the portability and simplicity of passive exoskeletons more than active exoskeletons for greater support. In addition, the responses to an open-ended question on "other characteristics that might influence adoption of exoskeletons" indicated that the exoskeleton should not negatively affect agility or introduce any risks for getting snagged.

In terms of safety and health risks that may be posed by use of exoskeletons (Figure 8), most participants expressed concern about getting snagged in brush (82%). Many respondents cited fear of reduced mobility causing hazardous situations (82%). Respondents also expressed potential fear about the loss of feeling from the ground, stab injuries, being trapped, malfunction, and weight stressing on the body (12% each).

### Potential barriers for exoskeleton use in forestry

Potential barriers identified can be classified into four aspects: financial, productivity, psychosocial, and physical aspects. The most important perceived barrier to the participants was productivity. Many participants were concerned about potential reduction in mobility and movement that may not only reduce productivity but also become a safety hazard. In addition, 47% of the participants stated that there would be some psychosocial barrier due to criticism or judgment from their peers, while 33% stated that there would be little to no barrier once the technology's efficacy was established. In terms of financial barriers, while there was a general consensus that initial cost

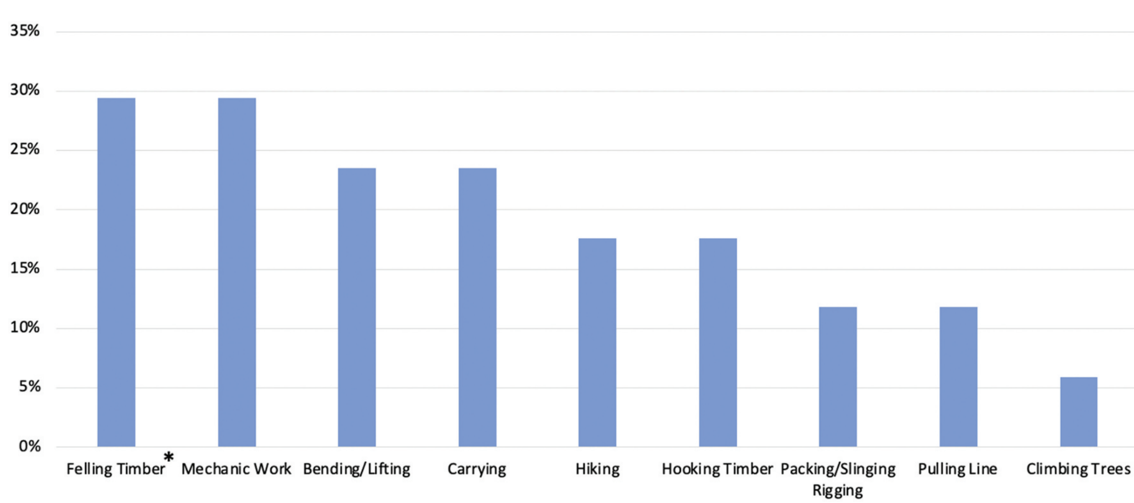


**Figure 6.** Potential tasks for exoskeletons (*N* =20). *Felling timber includes delimbing, bucking, and felling trees.

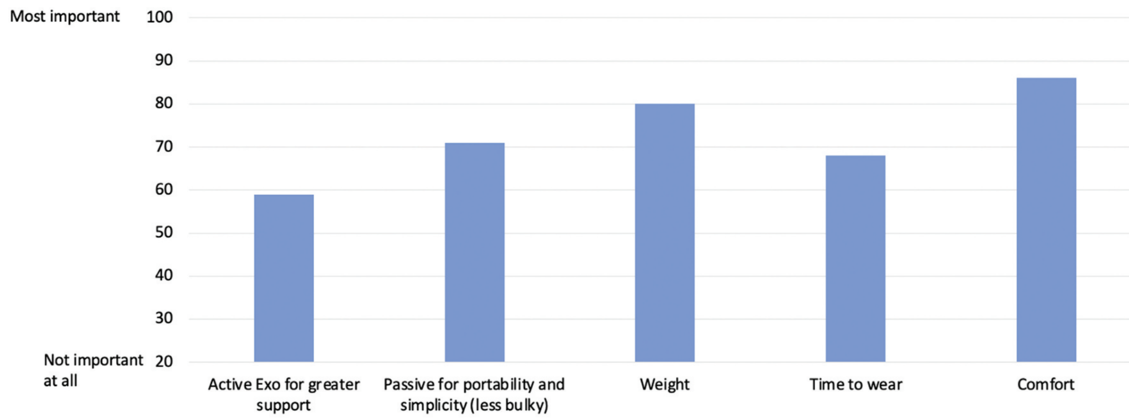


**Figure 7.** Importance of exoskeleton characteristics for accepting exoskeletons (*N* =20). The data show which exoskeleton design factors would affect forest workers' acceptance of exoskeletons.

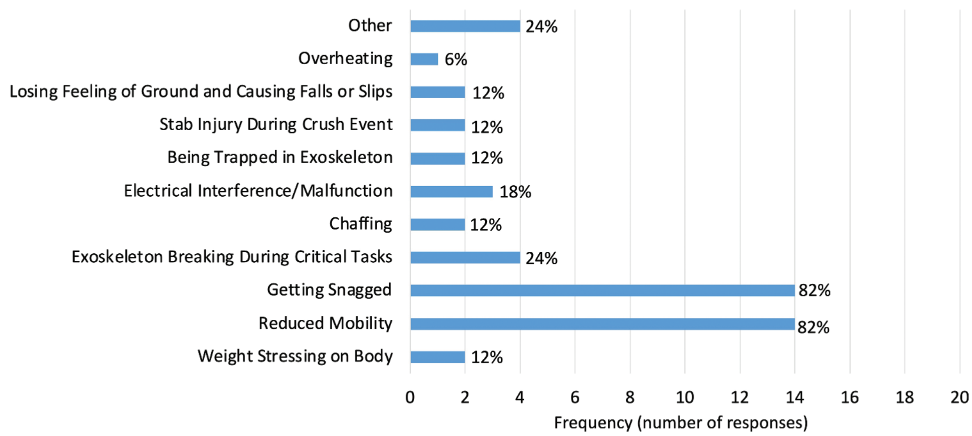


**Figure 8.** Potential safety and health risks that may be posed by the exoskeleton use (*N* =20).

and maintenance should be affordable, most of them stated that cost would be secondary to effectiveness and usefulness.

## Discussion

The aim of this study was to characterize musculoskeletal stress of timber fellers, evaluate forestry professionals' awareness and acceptance of exoskeletons, and identify important adoption factors, barriers/facilitators, and potential tasks for exoskeleton use. The results revealed that manual timber felling posed significant musculoskeletal stress in the back and shoulders. This finding suggests that back-support and upper-limb support exoskeletons may be suitable to the forest industry. Moreover, the study results consistently suggested that the forestry professionals had considerable interest and acceptance level in exoskeleton use as long as the important adoption factors are adequately addressed. The results also showed that timber felling, cutting/sawing, and mechanic work will benefit most from using exoskeletons.

### *Musculoskeletal stress and pain*

The biomechanical assessment showed that torso flexion (up to 45.4°) was substantial during manual timber felling. A previous study showed that the torso flexion of 20° or greater increased risks for low back injuries (Punnett et al. 1991; Keyserling et al. 1992). Moreover, this study demonstrated that manual timber felling was associated with considerable arm elevation (61.8°). Previous studies suggested that the upper-arm elevation (shoulder flexion) of 60° or greater could increase risks for shoulder injuries (Bernard 1997). These results suggest that biomechanical stress in the low back and shoulders may be substantial during manual timber felling. Therefore, exoskeletons designed to support back and upper limbs can have the potential to reduce injury risks in forestry workers.

These substantial biomechanical stresses in the low back and shoulders were in line with self-reported musculoskeletal pain measures. Based on the 10-point scale, the low back pain level was considered as "moderate pain" (Bieri et al. 1990). Twelve out of 13 forestry workers (92%) reported low back pain, and seven (54%) reported moderate low back pain (4–6 in the 10-point scale). Five participants reported mild low back pain (1–2 in the 10-point scale). This prevalence of the low back pain is substantially higher as compared to that (39%) of the total population in the U.S. (Lucas et al. 2021). Pain in the shoulders, wrist/forearm, and knees were also highly prevalent (85%). The pain prevalence in the upper and lower extremities appeared to be considerably higher compared to the upper and lower extremity pain prevalence (31 and 37%, respectively) of the general adult population in the U.S. (Lucas et al. 2021). Both objective biomechanical stress measures and self-reported pain outcomes consistently suggest that evaluating exoskeleton supporting low back, knee, and upper extremities would be a reasonable first step in a future study.

### *Exoskeleton characteristics and health risks for accepting exoskeletons*

This study identified important exoskeleton characteristics for forestry professionals to accept exoskeletons. The results indicate that exoskeletons should be practical, simple, and easy to use and maintain in forestry settings. Also, based on the collected data, exoskeletons should be affordable through incentives or reduced insurance premiums to facilitate broader adoption in forest industry. These important scores obtained from the forest industry were similar to those found previously in the agriculture industries (Upasani et al. 2019). These results indicate that passive exoskeletons, which are lighter, simpler in structure, and more portable than active exoskeletons, may be good candidates when considering exoskeleton evaluation and implementation in forestry.

A previous study also showed that agricultural workers expressed concerns about getting caught in farming equipment and falling (Upasani et al. 2019). These concerns are in line with previous experimental studies that investigated the effects of exoskeletons (Schiffman et al. 2008; Spada et al. 2017). Therefore, future studies should rigorously evaluate the potential positive and negative effects of exoskeletons on those risks associated with forestry work, such as the risk of getting snagged and reduced balance, before implementing exoskeleton in the forest industry. This will ensure that the benefits of exoskeletons as an ergonomic control outweigh any potential risks and promote their safe and effective use in forestry.

### *Potential barriers for exoskeleton use in forestry*

The results showed that the most important perceived barrier for exoskeleton use in forestry was productivity and reduced mobility. Therefore, the exoskeleton should neither interfere with forestry workers' motion nor compromise their physical capability. This was in-line with the important factors and potential safety hazards for exoskeleton adoptions discussed earlier. Nonetheless, most participants stated that this productivity issue could be mitigated with adequate training programs. While financial barriers are important among forestry professionals, the financial barriers would be secondary as long as exoskeletons are useful and effective in reducing musculoskeletal stress. Despite some potential concerns, the participants were generally positive about the exoskeletons. If the aforementioned concerns were addressed and the exoskeletons were available for them, most of the participants expressed that they would frequently use the exoskeletons.

### *Study limitations*

While this study provides important implications as it is the first to objectively quantify biomechanical stress of professional timber fellers during actual timber felling operation and evaluate forest workers' perspectives on exoskeletons, it has a few noteworthy limitations. First, as the field-based sensor study was conducted in limited geological regions (Oregon and Idaho) with a small sample size ($N = 10$), the results may not be generalizable to other regions with different forest types and terrain. As this study demonstrated the feasibility of objective biomechanical assessment using wearable sensors in a forest setting, it may be merited for future research to study a broader range of work environments with a larger sample size. Second, the response rate of the survey was not available as it was not possible to count how many forestry professionals were contacted by our industry partners who shared the survey invitation link with their contacts and listservs. Due to the lack of response rate, we were unable to evaluate potential bias such as selection bias and nonresponse/response bias. As many forestry professionals work independently, it is extremely difficult to measure the potential population (i.e. number of people reached). Nonetheless, our survey results were based on the participants with the various job titles and from four different states (Oregon, Idaho, Washington, and Montana), and the results may still provide important perspectives of forestry professionals.

## Conclusions

This study focused on quantification of biomechanical stress of timber fellers and assessment of forestry professionals' awareness and acceptance of exoskeletons. The study results revealed that forest workers have high prevalence of musculoskeletal pain especially in the low back and shoulder, which was substantially higher than pain prevalence of the general population. Such high prevalence of low back and shoulder pain was in line with the awkward back and shoulder postures measured using the wearable sensors during manual timber felling. These results indicate that back- and arm-support passive exoskeletons would be appropriate types for initial testing of efficacy for the forest industry. Moreover, the results identified perceived barriers/risks (weight, comfort, reduced agility/mobility) and preference (simplicity/portability over greater support) related to the adoption of exoskeletons in forestry. The forestry professionals' input also helped identify potential targeted tasks for exoskeletons: timber felling, cutting/sawing, and mechanic work. The study results consistently indicate that there is substantial interest and acceptance level of exoskeletons in the forest industry. While exoskeletons have been recognized as an emerging control measure to reduce musculoskeletal disorders in various industries, its readiness and applicability in forestry have not been evaluated. This study provides important insights for future studies investigating the feasibility, readiness, and effectiveness of exoskeletons to be applied to the forest industry. Based on the pain prevalence, biomechanical stress, and perspectives of forestry workers evaluated in this study, a series of future studies are planned to evaluate commercially available exoskeletons in both laboratory and field settings. These studies will focus on exoskeletons that satisfy the adoption factors and design characteristics for timber harvesting operations. Through rigorous assessment of the efficacy of these exoskeletons, future studies aim to identify and implement them as potential control measures to improve the safety and health of forestry workers.

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