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Report to the Ranking Member
Committee on Health, Education, Labor and Pensions
U.S. Senate

December 2024

TECHNOLOGY ASSESSMENT

Accessible Version

Wearable Technologies

Potential Opportunities and Deployment Challenges in Manufacturing and Warehousing

GAO-25-107213

The cover image depicts workers using wearable technologies in the workplace. Workers in automotive manufacturing facilities can wear arm-support exoskeletons to reduce muscle fatigue while working on the underside of a vehicle. Workers in warehousing facilities can wear ergonomic sensors designed to detect postures or motions that could cause injury.

Cover source: GAO (illustration). | GAO-25-107213

TECHNOLOGY ASSESSMENT

Highlights of GAO-25-107213, a report to the Ranking Member of the Committee on Health, Education, Labor and Pensions, U.S. Senate

December 2024

Why GAO did this study

In 2021, musculoskeletal injuries cost employers at least $17.7 billion. Workers in manufacturing and warehousing experienced these injuries at higher rates than all of private industry. Companies are investigating wearables as one option for injury prevention. Wearables that may help reduce musculoskeletal injuries include exoskeletons, which aim to relieve strain in specific muscle groups, and ergonomic sensors, which analyze posture to identify possible injury risks.

GAO was asked to assess the use of wearables in industrial workplaces and their effect on workers. This report discusses (1) the extent to which select wearable technologies affect worker safety, (2) challenges that exist for deployment of wearable technologies in the workplace, and (3) associated ongoing activities that stakeholders are currently undertaking to help address the challenges.

In conducting this assessment, GAO reviewed relevant literature; interviewed federal officials, academic researchers, wearables manufacturers, private companies with experience deploying wearables, a nonprofit organization, and worker organizations; conducted two visits to sites deploying wearables; and attended a conference on ergonomics.

View GAO-25-107213. For more information, contact Karen L. Howard, PhD, at (202) 512-6888 or HowardK@gao.gov.

Wearable Technologies

Potential Opportunities and Deployment Challenges in Manufacturing and Warehousing

What GAO found

Certain wearable technologies (wearables) may provide some benefits to workers experiencing musculoskeletal pain or discomfort, such as back pain, but GAO found limited evidence to support wearables' ability to reduce injuries. GAO examined the effects on worker safety of two of the most commonly deployed wearable technologies in manufacturing and warehousing: exoskeletons and ergonomic sensors.

Illustration of automotive manufacturing workers wearing arm-support exoskeletons

Source: GAO (illustration). | GAO-25-107213

Exoskeletons are designed to reduce muscular fatigue and injuries by providing support to specific muscle groups. Laboratory studies generally show that exoskeletons can reduce muscle strain in a controlled environment. Deployments in the workplace, however, have produced limited public studies demonstrating a reduction in worker injuries, in part due to the short duration of many field studies.

Ergonomic sensors are designed to detect postures or motions that could cause injury. Ergonomic sensor manufacturers have self-reported case studies with improved safety outcomes. GAO, however, found limited evidence that current ergonomic sensors improve worker safety, in part because multiple factors contribute to musculoskeletal injuries and posture measurements alone may not accurately predict risk.

Stakeholders have described several challenges from their past experiences deploying exoskeletons and ergonomic sensors. For example:

- Workers expressed concerns about the practicality of wearables. Workers are more likely to use wearables that are comfortable and convenient for their jobs.
- Warehousing and manufacturing company representatives expressed that they may prefer to deploy other injury hazard controls—such as elimination or substitution—before considering wearables. For example, providing a lift table to eliminate a worker's need to lift objects may be more effective at preventing injuries than using a back-support exoskeleton.
- Many stakeholder groups voiced concerns about data that some wearables may collect, particularly regarding data ownership, privacy, and security.

The wearables market is evolving quickly. Stakeholders told GAO they need more time to assess how well ongoing efforts address these challenges. GAO identified a set of ongoing activities that stakeholder groups (such as wearables manufacturers and companies interested in deploying wearables) are undertaking. These activities include collecting additional data on accuracy and efficacy of wearables and gathering worker feedback as wearables are deployed. Additionally, national consensus committees are currently developing standards to address these challenges. Stakeholders told GAO that continuing these activities may address current challenges and did not favor other policy actions, such as additional standards and regulations.

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Abbreviations

- BLS: Bureau of Labor Statistics
- MSD: musculoskeletal disorder
- NAICS: North American Industry Classification System
- NIOSH: National Institute for Occupational Safety and Health
- OSHA: Occupational Safety and Health Administration
- OSH Act: Occupational Safety and Health Act of 1970
- PPE: personal protective equipment
- REBA: Rapid Entire Body Assessment
- RULA: Rapid Upper Limb Assessment
- SOII: Survey of Occupational Injuries and Illnesses
- Wearables: wearable technologies

U.S. GOVERNMENT ACCOUNTABILITY OFFICE
441 G St. N.W.
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December 12, 2024

The Honorable Bill Cassidy, M.D.
Ranking Member
Committee on Health, Education, Labor and Pensions
United States Senate

Dear Dr. Cassidy:

In manufacturing and warehousing, musculoskeletal injuries are prevalent, damage workers' quality of life, and are costly to employers. For these reasons, occupational health and safety professionals are looking for new ways, such as using wearable technologies, to try to reduce or prevent musculoskeletal injuries from occurring.[1] According to data from the U.S. Department of Labor's Bureau of Labor Statistics (BLS), manufacturing and warehousing workplaces experienced higher rates of musculoskeletal injuries that resulted in missed workdays with or without job transfer or job restriction than all private industry from 2011 through 2020.[2] BLS also reported that warehouse workers experienced musculoskeletal injuries at almost five times the rate for all of private industry from 2021 through 2022 (see fig. 1),[3] and we recently found that these injuries may be underreported by employers and workers.[4] According to a 2024 assessment by a workers' compensation insurance provider in the U.S., musculoskeletal injuries cost employers at least $17.7 billion in 2021, and overexertion involving outside sources, such as lifting or carrying an object, resulted in the greatest workers' compensation losses for manufacturing and warehousing.[5]

[1]The Bureau of Labor Statistics (BLS) refers to musculoskeletal injuries as musculoskeletal disorders (MSDs). MSDs include injuries and illnesses such as pinched nerves, herniated discs, sprains, strains, tears, carpal tunnel syndrome, and other connective tissue diseases and disorders when the event or exposure leading to the injury or illness is overexertion and bodily reaction, overexertion involving outside sources, or repetitive motion involving microtasks.

[2]In this report, we use the term warehousing as a shorthand for the formal BLS category of warehousing and storage.

[3]BLS defines industry sectors using the North American Industry Classification System (NAICS), which includes 20 broad industry sectors including warehousing and manufacturing. BLS defines private industry as businesses owned by individuals or groups of individuals. BLS reports nonfatal injury data, including MSDs, in the Survey of Occupational Injuries and Illnesses (SOII). Beginning in November 2023, BLS began releasing the SOII case characteristic and worker demographic data, which includes MSDs, biennially and so the most recent data available are from 2021 through 2022.

[4]See GAO, *Workplace Safety and Health: OSHA Should Take Steps to Better Identify and Address Ergonomic Hazards at Warehouses and Delivery Companies*, GAO-24-106413 (Washington, D.C.: Sept. 18, 2024) for additional information.

[5]Liberty Mutual Insurance, *Workplace safety indices: insights and methodology* (Boston, MA: Liberty Mutual Insurance, 2024). GAO did not evaluate the quality of the methodology used to calculate the cost of musculoskeletal injuries to businesses. Musculoskeletal injuries include those caused by overexertion involving outside sources, other exertions or bodily reactions, and repetitive motions involving microtasks. We use warehousing as a shorthand for Liberty Mutual's category of transport and warehousing.

Figure 1: Incidence rates of musculoskeletal injuries in warehousing and manufacturing compared to all of private industry, 2021-2022

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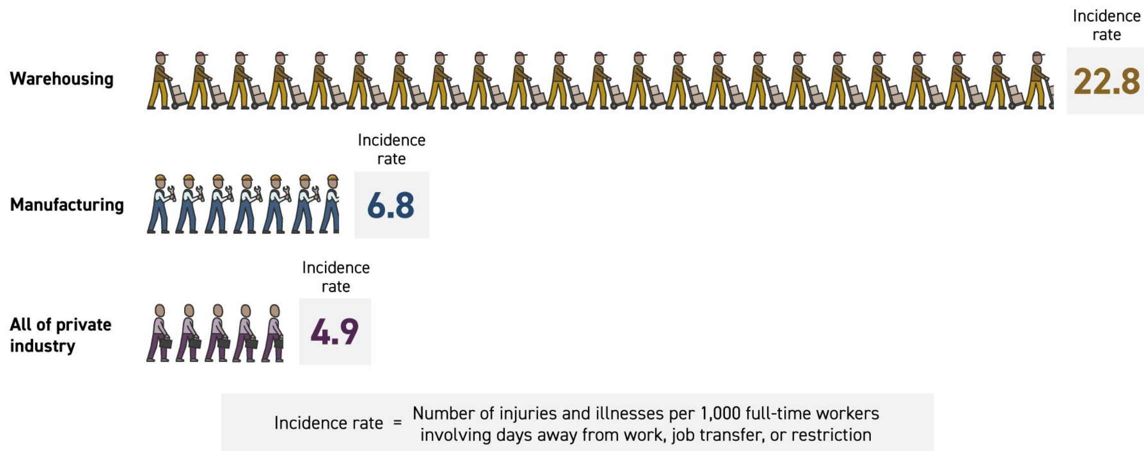

Sources: GAO (analysis and icons); Bureau of Labor Statistics (data). | GAO-25-107213

Note: Bureau of Labor Statistics defines private industry as employment in businesses owned by individuals or groups of individuals. The private industry incidence rate includes warehousing and manufacturing. BLS quotes the following relative standard errors for each incidence rate: 2.5 percent for warehousing, 0.8 percent for manufacturing, and 0.5 percent for private industry.

Some manufacturing and warehousing companies have begun exploring wearable technologies (wearables) as an option to help prevent musculoskeletal injuries. In our previous work,[6] we found that exoskeletons and ergonomic sensors are two of the most deployed wearables to address musculoskeletal safety in manufacturing and warehousing.[7] Exoskeletons are devices worn around the body to support a worker's arms, legs, back, hand, or use of tools. Ergonomic sensors, types of wearable sensors also known as inertial measurement units, are compact sensors designed to detect postures or motions that could cause injury. In addition to body movements, ergonomic sensors may also monitor external factors, such as environmental noise. As these technologies develop and interest in them grows, questions persist about their effects on injury reduction. For example, we recently described how some wearables may both improve safety and have unintended safety consequences for workers.[8]

You asked us to assess the use of wearable technologies in industrial workplaces and their effect on workers. This report discusses (1) the extent to which select wearable technologies affect worker safety, (2) the challenges that exist for deployment of wearable technologies in the

[6]GAO, *Science & Tech Spotlight: Wearable Technologies in the Workplace*, GAO-24-107303 (Washington, D.C.: Mar. 4, 2024).

[7]We consider a company to have deployed wearables if it has tested, piloted, or implemented wearables with its workers.

[8]GAO-24-106413.

workplace, and (3) associated ongoing activities that stakeholders are currently undertaking to help address the challenges. We are focusing our discussion on exoskeletons and ergonomic sensors deployed in the manufacturing and warehousing workplaces. See appendix I for a full discussion of the objectives, scope, and methodology.

We conducted our work from January 2024 through December 2024 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

1 Background

1.1 Work-related musculoskeletal injuries and ergonomics

Work-related musculoskeletal injuries, which affect muscles, nerves, tendons, joints, cartilage, and spinal discs, can damage workers' quality of life and be costly to companies. The Department of Labor's BLS defines musculoskeletal injuries as those resulting from bodily reaction (e.g., bending, climbing, crawling, reaching, and twisting), overexertion, or repetitive motion (e.g., leaning to reach items, lifting boxes, and working overhead on assembly lines). The National Institute for Occupational Safety and Health (NIOSH) of the Department of Health and Human Services has recognized work-related musculoskeletal injuries as a type of injury since 1997. These injuries are conditions in which: (1) the work environment and performance of work contribute significantly to the injury or (2) the injury is made worse or persists longer due to work conditions. Work-related musculoskeletal injuries can affect a worker's ability to perform job functions (e.g., lifting) and enjoy activities outside of work. Work-related musculoskeletal injuries are also associated with high costs to employers through absenteeism and lost productivity, as well as increased health care, disability, and workers' compensation costs. For example, according to one analysis, back-related musculoskeletal injuries were associated with the highest cost to employers compared to other body part injuries.[9]

Although musculoskeletal injuries may develop quickly when workers are required to perform very hazardous work for many hours a day, musculoskeletal injuries can also take long periods of time before they become observable. One stakeholder pointed out that a musculoskeletal injury that results in a workers' compensation claim could take 5 to 10 years to develop, and it may have already begun developing prior to the implementation of wearables or other controls.[10]

1.2 Hierarchy of controls and wearables

Occupational health and safety professionals and ergonomists use a framework called the hierarchy of controls when considering which actions may best reduce workplace hazards or mitigate workers' exposure to those hazards, including those that lead to work-related musculoskeletal injuries. NIOSH developed the hierarchy of controls as a reference for companies seeking to reduce the risk of workplace injuries.[11] As shown in figure 2, NIOSH includes five levels of actions a company can take to reduce or remove hazards or mitigate exposure, listed from most to least effective (top to bottom).

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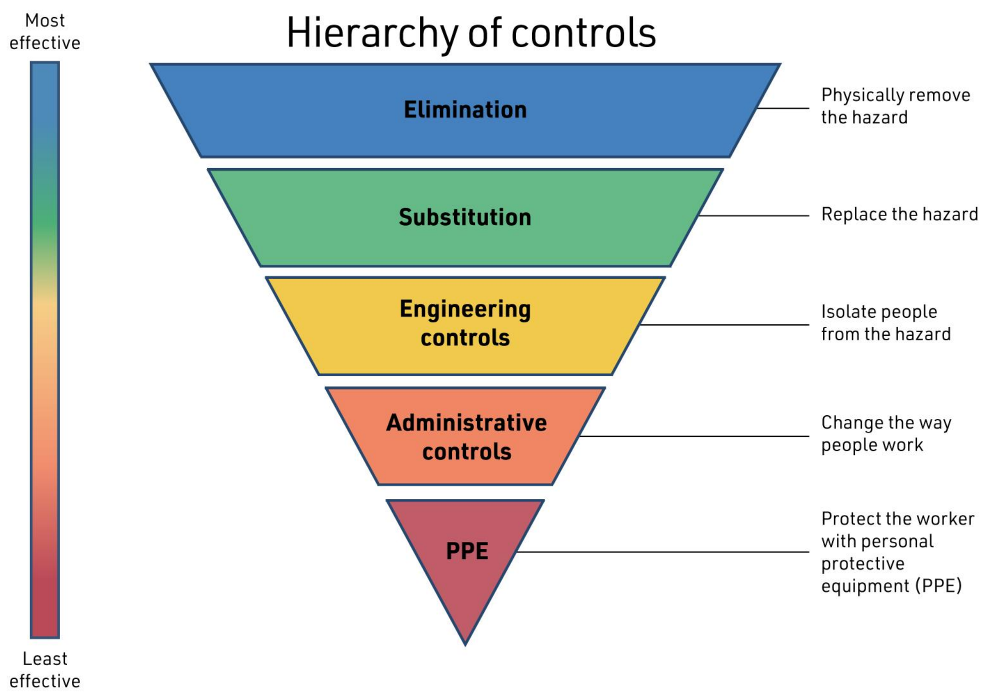
[9]Liberty Mutual Insurance, *Workplace safety indices.*

[10]Stakeholders can include wearables manufacturers, deploying companies, occupational health and safety professionals, worker organizations, academic researchers, government agencies, and a workplace safety nonprofit institution. See appendix I for more information.

[11]NIOSH, "About Hierarchy of Controls," (Jul. 31, 2024), https://www.cdc.gov/niosh/hierarchy-of-controls/about/index.html.

Figure 2: The hierarchy of controls to reduce or remove workplace hazards

Figure 2: The hierarchy of controls to reduce or remove workplace hazards



Source: GAO adaptation of National Institute for Occupational Safety and Health figure. | GAO-25-107213

The five levels of actions are categorized and organized by effectiveness, but the most effective mitigations may not be the easiest to implement into existing processes. **Elimination**—physical removal of the hazard at the source—is the most effective and preferred way to mitigate risks but is best to implement at the development stage of a work process. Elimination could include automating a hazardous task so that a worker does not have to perform it. The next preferred method in the hierarchy of controls is **substitution**—using a safer alternative to the hazard, such as using an automated tool instead of a manual one. Next, **engineering controls** involve redesigning work—such as implementing protective barriers—to isolate workers from a hazard. **Administrative controls** establish work practices—such as job rotations—that reduce the duration, frequency, or intensity of a worker's exposure to a hazard. Finally, providing **personal protective equipment (PPE)** to minimize exposure to hazards is considered the least effective control and includes providing a worker with protective equipment—such as safety glasses—to reduce exposure to the hazard while performing the task. PPE can be effective at reducing hazard exposures, but only when employers and workers use it correctly and consistently.

Occupational health and safety professionals said they generally consider wearables as either administrative controls or PPE. Because NIOSH's hierarchy of controls considers these the least effective hazard reduction tools, companies interested in deploying wearables might choose to also consider more effective safety controls, such as elimination or substitution.

1.3 Current federal agency roles for musculoskeletal injuries and wearables

Two federal government agencies—NIOSH of the Department of Health and Human Services and the Occupational Safety and Health Administration (OSHA) of the Department of Labor—currently have small but important roles related to wearables in workplaces. NIOSH conducts research on and makes recommendations for the prevention of work-related injury and illness. In this role, NIOSH funds studies to assess the feasibility and long-term effects of wearables in the workplace and educates health and safety personnel about implementation of new technologies, such as wearables. NIOSH officials said that the agency does not currently test the accuracy of wearables, but it does certify other devices such as respirators.[12]

OSHA's mission is to ensure American workers have safe and healthful working conditions and are free from unlawful retaliation by employers. OSHA carries out this mission, in part, by setting and enforcing workplace safety and health standards. While OSHA does not have a specific standard for ergonomic hazards that cause musculoskeletal injuries, it addresses ergonomic hazards through enforcement of the general duty clause.[13] We recently found, however, that OSHA rarely identifies and addresses ergonomic hazards at warehouses due to several challenges. We provided several recommendations to address this finding.[14] OSHA also does not have standards for emerging technologies, including exoskeletons, ergonomic sensors, or other wearables. OSHA officials said they may note the use of technologies, such as wearables, that they observe while inspecting workplaces and that OSHA has not received reports of any injuries directly attributable to the use of wearables.

[12] *See*, 42 C.F.R. Part 84 for the procedures and requirements for approval of respiratory devices.

[13] Section 5(a)(1) of the Occupational Safety and Health Act of 1970 (OSH Act), known as the general duty clause, requires employers to provide a work environment free from recognized hazards that are causing or are likely to cause death or serious physical harm. 29 U.S.C. § 654(a)(1). A specific standard OSHA issued in 2000 to protect workers from ergonomic hazards was reviewed and disapproved by Congress under the procedures of the Congressional Review Act, 5 U.S.C. § 802(a). Ergonomics Program, 65 Fed. Reg. 68,262 (Nov. 14, 2000) was disapproved by Joint Resolution, Pub. L. No. 107-5, 115 Stat. 7 (Mar. 20, 2001).

[14] GAO-24-106413.

2 Data Gaps and Efficacy Limitations Hinder Understanding of the Effects of Wearables on Worker Safety

Current data offer limited evidence demonstrating the long-term efficacy of exoskeletons and ergonomic sensors to reduce injuries and improve worker safety. Current publicly available studies we reviewed did not find definitive measurable safety results in the field from deployments of exoskeletons. Laboratory studies, however, offer encouraging data that exoskeletons can reduce muscle strain and may, over time, help prevent injuries. Ergonomic sensors can offer diagnostic information about some injury risks, but studies have not demonstrated that this information can improve worker safety due to multiple limitations, including sensor accuracy.

2.1 Despite gaps in current deployment data, exoskeletons show some potential to reduce injuries

2.1.1 Principles of operation

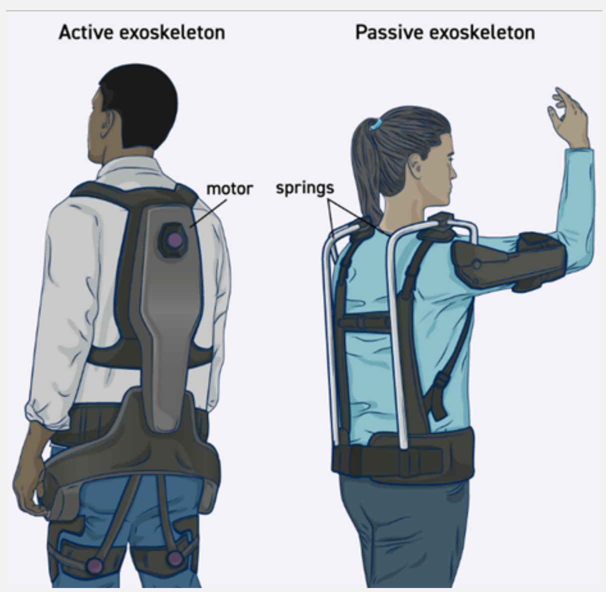
Exoskeletons are designed to reduce muscular fatigue and injuries. The exoskeleton provides support to particular muscle groups, such as the shoulders or lower back, to help reduce muscle strain. In turn, this strain reduction may reduce muscle fatigue and make workers less likely to sustain musculoskeletal injuries. Exoskeletons can be active, meaning they use battery-powered motors to assist the muscles and augment the strength of the wearer, or passive, meaning they are not battery powered and instead use springs and dampers to support the wearer (see text box).

Passive and active exoskeletons

Exoskeletons can be passive or active, depending on whether the system uses an onboard battery. Passive systems have springs and dampers that provide a counterforce to relieve the strain on targeted muscle groups, such as a worker's shoulders. Some models include an adjustment to change the tension and provide more or less support.

By contrast, active systems use battery-powered motors in the suit to adjust the level of support depending on the worker's movements. For example, an active suit can vary support depending on how fast the worker moves to make a lift or bend. In general, active exoskeletons are designed for heavier-than-normal lifts, but these devices also tend to weigh and cost more.

In our site visits and discussions with deploying companies, we found they predominantly used passive exoskeletons, but some stakeholders noted that active systems may be deployed more frequently outside the U.S. In particular, one manufacturer of active exoskeletons said they have deployed systems primarily in Europe and had only recently begun to expand to the U.S. market.



Source: GAO (analysis and illustration). | GAO-25-107213

According to our research, companies have predominantly deployed passive arm- and back-support exoskeletons in industrial workplaces. Table 1 shows the varieties of commercially available passive and active exoskeletons and some examples of their use, according to market data from one exoskeleton trade publication. According to this publication's market data, the types of exoskeletons with the highest number of models on the market are arm- and back-support exoskeletons. Two companies we spoke with that had tested or deployed exoskeletons also noted they worked predominantly with arm and back exoskeletons, because of technical maturity and use cases for their industries.

Table 1: Commercially available exoskeletons and their uses as reported in an online trade publication

Exoskeleton type	Power source	Number of models[a]	Use case
Arm support	Passive	22	Shoulder support (e.g., underbody automotive work)
Arm support	Active	5	Shoulder support (e.g., using power tools overhead)
Back support	Passive	37	Reduce load on back when repetitively lifting (e.g., picking items in a warehouse)
Back support	Active	13	Reduce load on back when lifting heavy objects (e.g., heavy lifting in the logistics industry)
Leg support	Passive	5	Reduce load on knees when crouching and squatting (e.g., cement laying)
Leg support	Active	3	Supports and aids movement of knees and hips (e.g., lifting heavy equipment)
Hand support	Active	2	Grip support for repetitive tasks (e.g., using power tools for extended periods of time)
Tool support	Active	2	Offload the weight of a heavy tool (e.g., drilling overhead)

Source: GAO analysis of market data from Exoskeleton Report. | GAO-25-107213

[a]The number of each type of exoskeleton on the market was determined from market research from the trade publication Exoskeleton Report as of October 7, 2024.

2.1.2 Efficacy

Laboratory studies generally show that exoskeletons can reduce muscle strain, but these results have not translated in the same degree to measured safety benefits—such as a reduction in injuries—in the field. A variety of laboratory studies have tested the ability of exoskeletons to reduce muscle strain, typically by using electrical sensors to measure muscle exertion of a prescribed series of tasks with and without the exoskeleton. According to our review of studies, researchers have measured muscle strain reductions from 7 to 87 percent when using exoskeletons.[15] This large range reflects reductions in strain on the specific muscles of individual subjects recorded by sensors that measure muscle activity. Reductions also varied by exoskeleton design and activity type. Two studies saw no reduction in strain, but generally the studies we reviewed showed some strain reduction in this range. One exoskeleton researcher concurred that, according to his research and review of literature, laboratory studies generally found that exoskeletons can reduce muscle strain.

Despite the encouraging laboratory results, deploying companies and researchers have found limited evidence of measurable safety results in the field. According to our literature review and conversations with stakeholders, neither laboratory nor field studies have shown definitive evidence that exoskeletons reduce injuries. As one study highlighted, the magnitude of benefits seen in laboratory results may overestimate the effects in the field. Some deploying companies reported positive early signs of potential injury reduction from exoskeleton use, such as successful small trials, reduced worker discomfort, and fewer medical visits. Representatives from one of those companies, however, said their internal trials have not conclusively shown a reduction in injuries. Possible causes for the limited evidence of measurable safety results include:

Limited long-term studies. Deploying companies and researchers may need more time to measure a safety outcome from exoskeletons. Ergonomic injuries develop over years, and measuring an improvement in safety can thus require years of data collection, while many existing field trials last only a month or less. In addition, researchers and deploying companies may struggle to maintain and track user participation over this extended period as workers discontinue exoskeleton use, change to work tasks that do not require an exoskeleton, or leave the company. As of February 2024, the longest field study we identified in the literature on exoskeletons followed employees at an automotive manufacturing plant over 18 months.[16] While the study showed that the users of arm-support exoskeletons made fewer medical visits involving upper extremity injury or pain than those in the control group, significant participant dropout impacted the certainty of their findings. Thirty-seven

[15]Our literature review identified eight laboratory studies of which six demonstrated some strain reduction. The two additional studies did not demonstrate any strain reduction. See appendix I for details on our literature review.

[16]Sunwook Kim, Maury A. Nussbaum, and Marty Smets, "Usability, User Acceptance, and Health Outcomes of Arm-Support Exoskeleton use in Automotive Assembly: An 18-Month Field Study," *Journal of Occupational and Environmental Medicine*, vol. 64, no. 3 (2022), https://doi.org/10.1097/JOM.0000000000002438.

percent of participants in the exoskeleton group and 38 percent of the control group left the study due to reasons such as job transfers and loss of interest.

Even when companies can conduct long-term studies, they can find it difficult to isolate the effects of an exoskeleton on worker's safety. Over the course of years in the workplace, workers might change job tasks that will affect their risk of injury. In addition, companies will likely implement multiple complementary safety measures, which makes it difficult to determine whether any improved safety outcome can be attributed solely to using exoskeletons.

Differences in field and laboratory conditions. Results from laboratory tests do not necessarily transfer to the field due to the limitations of laboratory environments. Laboratory-based studies we reviewed tended to use participants with no experience in manufacturing or warehousing jobs, occur within highly controlled environments, and involve simulated tasks, such as lifting a box. These factors do not negate the studies' findings but raise questions about how well exoskeletons might work among a more representative population or in a more dynamic warehousing or manufacturing environment.

Researchers also face greater challenges when measuring the effects of exoskeletons on workers in the field. Rather than measuring muscle strain directly, researchers may need to rely on worker questionnaires on topics such as perceived comfort, fit, and job performance when using the exoskeleton. This may be necessary because the electrical sensors used to measure muscle strain are difficult to interpret in the field. The absence of quantitative physiological data could make it more difficult to understand the potential safety effect of exoskeletons in the field.

Collecting data on usage patterns also posed a challenge to researchers. According to one study, some participants may have used their exoskeletons for a few hours a day or a couple of days per week, while others may have used their exoskeletons for the entire workday, but the researchers did not have adequate data on that usage.[17] The authors noted that the absence of data on the frequency of exoskeleton use can make it difficult to quantify the benefits and limitations of the exoskeleton use for worker safety.

2.2 Ergonomic sensors can provide some information but have demonstrated limited efficacy and accuracy

2.2.1 Principles of operation

Ergonomic sensors measure the body's orientation and use algorithms to analyze whether workers enter postures that might put them at risk for injury.[18] Usually worn on the back, hip, or arm, one common ergonomic sensor measurement involves measuring the angle the body creates in a

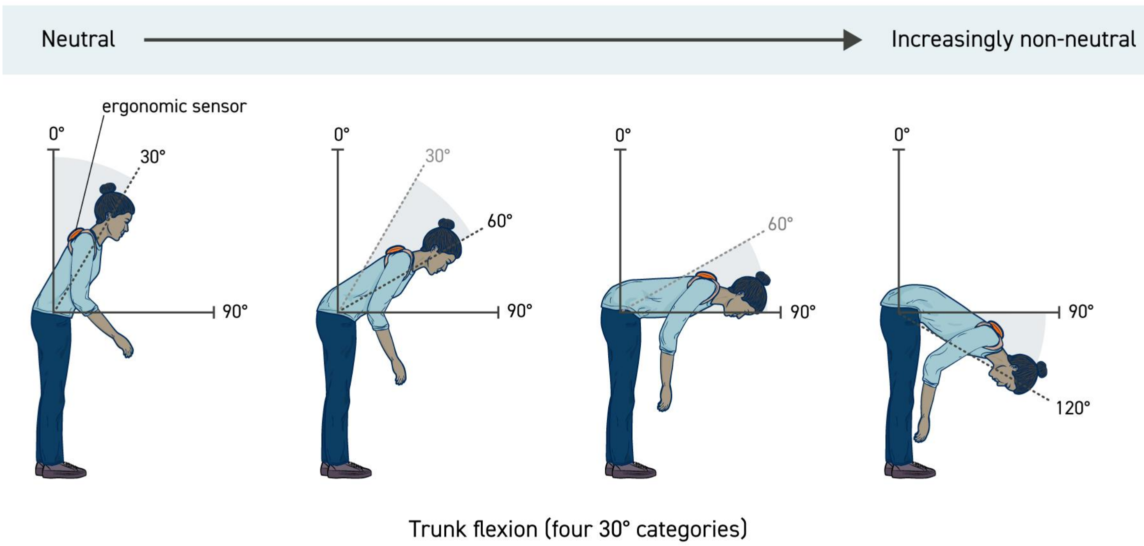
[17] Kim, Nussbaum, and Smets, "Usability, User Acceptance, and Health Outcomes," 209.

[18] Ergonomic sensors measure acceleration, rotation, and magnetic fields to infer motion and orientation. These sensors are sometimes known as inertial measurement units.

forward bend at the hips (fig. 3).[19] Ergonomists regularly use posture as a risk factor for potential injury when analyzing job tasks. For example, it is commonly accepted that as a worker bends farther forward and assumes an increasingly non-neutral posture, the muscle strain on the lower back increases, as does the risk of musculoskeletal injury.[20]

Figure 3: Categorization of forward bends by the National Institute for Occupational Safety and Health

Figure 3: Categorization of forward bends by the National Institute for Occupational Safety and Health



Source: Adapted from Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, *Observation-based Posture Assessment: Review of Current Practice and Recommendations for Improvement*, 2014-131 (July 2014); GAO (illustration). | GAO-25-107213

While worn, ergonomic sensors continually monitor and collect data on the worker's posture to help infer injury risk. An ergonomist or occupational health and safety professional can analyze the ergonomic sensor data to determine to what extent and how often the worker is bending and whether this puts them at injury risk using ergonomics calculations.[21] An ergonomist can use this information to, for example, provide additional training to teach employees safer movements or modify the workspace to reduce or eliminate ergonomic risks.

Some ergonomic sensors include a feature to provide real-time feedback to the worker.

[19]While various ergonomic sensors may measure multiple body postures (forward bend, lateral bend, twisting, etc.), we highlight the forward bend to illustrate the principle of operation.

[20]NIOSH published a literature review evaluating the effect of workplace factors on musculoskeletal injuries and found, for example, that bending and extending into non-neutral postures generally increases injury risk. Department of Health and Human Services, NIOSH, *Musculoskeletal Disorders and Workplace Factors – A Critical Review of Epidemiologic Evidence for Work-Related Musculoskeletal Disorders of the Neck, Upper Extremity, and Low Back*, 97-141 (1997).

[21]Ergonomists can use a number of calculations to assess ergonomic risk, including the Rapid Upper Limb Assessment (RULA) and the Rapid Entire Body Assessment (REBA). See Department of Health and Human Services, NIOSH, *Observation-Based Posture Assessment: Review of Current Practice and Recommendations for Improvement*, 2014-131 (2014).

When the sensor detects a bend beyond a certain threshold—such as 60 degrees—the sensor will vibrate or emit an audible sound to alert the worker about potential for injury risk due to their posture.[22] Wearables manufacturers we spoke with expressed divided views on the efficacy of this real-time feedback. Some manufacturers felt the feedback provided the best tool to alert workers when they make risky movements and influence them to change their behavior. Another manufacturer said they did not include this feature because they believe workers are likely to disregard the feedback, and the manufacturer sees little evidence that real-time feedback can create lasting changes in worker behavior.

Unlike exoskeletons, ergonomic sensors require extra intervention—through data analysis and workplace modification, a real-time feedback system, or both—to potentially improve worker safety. The sensor alone does not, for example, prevent workers from bending too far or alleviate the strain of lifting in a forward bent position. Other posture analysis methods, such as when an ergonomist directly observes a task and manually measures body angles, also require extra intervention—these analyses only identify the possibility for risk of injury. Despite the need for further intervention, multiple experts noted that ergonomic sensors can help improve posture analysis by providing continuous measurement of posture over multiple days and removing bias associated with human measurement and observation.

2.2.2 Efficacy

We found limited evidence that current ergonomic sensors can improve worker safety. While wearables manufacturers have published case studies on improved safety outcomes, these studies are proprietary and manufacturers could not provide the underlying data for us to assess their validity.[23] For example, for one ergonomic sensor manufacturer, we reviewed five case studies which reported a reduction in risky bends and zero injuries over the course of 3 to 5 months. These case studies, however, lack key information required to assess the significance of their findings. For example, none of these studies reported a baseline rate of injuries before the introduction of the ergonomic sensor or used a technique such as comparing outcomes of workers in randomly assigned sensor user and control groups, which is necessary to determine the effect of the sensor on injuries. Furthermore, two deploying companies we spoke with that piloted ergonomic sensors reported they discontinued using ergonomic sensors. One warehousing company representative explained the decision to discontinue use by noting that when the company compared 6 months of data from workers using the ergonomic sensors to 6 months of data without use, the company saw no change in injury rates. In the research literature, we found six studies that assessed the

[22]Some ergonomic sensor manufacturers cited 60 degrees as the threshold their devices use to indicate increased risk. NIOSH guidance does not specify 60 degrees as a threshold of marked elevated risk but notes that risk generally increases with a more non-neutral posture.

[23]Improved safety outcomes in these case studies include a reduction of "risky" forward bends greater than 60 degrees or a reported reduction in injuries during a pilot study.

performance of ergonomic sensors for measuring posture in the field. None of the studies we identified, however, connected these results to a measured safety outcome (e.g., reduction in injuries, days off work, workers' compensation claims).

According to our review of available information, two explanations, discussed below, may account for the absence of measurable safety outcomes with ergonomic sensors.

Multiple ergonomic factors. In its review of research on musculoskeletal disorders, NIOSH identifies factors in addition to posture, such as force and speed of a movement, that also affect musculoskeletal injury risk. Multiple ergonomics experts also pointed to the multiple factors that influence injury risk. One researcher explained that while ergonomic sensors may detect the frequency with which a worker makes a risky bend, this does not necessarily correspond to the total injury risk. Rather, one single high-force lift from a bent position may cause an injury.

Given the multifaceted nature of injury risk and the short duration of studies to date, some experts highlighted the need for long-term studies to understand the extent to which ergonomic sensors can predict injuries. Longer multi-year studies could help improve understanding of which factors matter most for injury prevention, the risk thresholds for these factors, and how ergonomic sensors can affect injuries over time. At present, these studies do not exist.

Accuracy. Ergonomic sensors may not measure body posture accurately or consistently, which limits their ability predict injury. Multiple research studies and stakeholders we spoke to highlighted that accuracy can vary according to the number of sensors used (e.g., one sensor worn on the hip vs. sensors on the arm, hip, and back) and the software algorithms used to analyze the ergonomic data. Some commercial systems use just one sensor, which studies show can limit accuracy. The industrial environments where workers use the sensors can also degrade accuracy. For example, one study found that while incorporating magnetometers into sensors can improve the accuracy, these signals can be distorted due to interference from the materials present in industrial workplaces.[24] Despite these limitations, some research studies have shown the ability to improve system accuracy with improved algorithms—such as those using machine learning.

Despite these challenges, some deploying companies and other stakeholders see value in ergonomic sensors to provide diagnostic information or in applications beyond posture monitoring. For example, one research group demonstrated the ability to process data from ergonomic sensors to determine worker proximity to slip, trip, and fall risks. Additionally, some ergonomic sensor manufacturers have begun including other safety components, such as location sensors to prevent collisions with heavy machinery (e.g., forklifts).

[24]Magnetometers are used in ergonomic sensors to measure Earth's magnetic field to help determine orientation. Francesco Pistolesi and Beatrice Lazzerini, "Assessing the Risk of Low Back Pain and Injury via Inertial and Barometric Sensors," *IEEE Transactions on Industrial Informatics*, vol. 16, no. 11 (2020).

3 Deployment of Wearables Raises Several Challenges

As discussed in the prior sections, companies have begun deploying wearables and gathering information on the resulting benefits and challenges. The wearables market, however, is evolving quickly and may outpace the speed of a company's deployment protocols and acquisition of data on safety effects. Stakeholders have described several challenges for wearables from experiences with initial deployments. These challenges are comfort, convenience, identifying appropriate jobs, identifying appropriate controls, limited efficacy data, data ownership, data privacy, the evolving market of wearables, and worker burdens. We have organized these challenges below by those raised by workers, those raised by deploying company representatives, those concerning data, and those that may arise in the future.

3.1 Challenges raised by workers

Comfort. If a wearable is not comfortable, workers will not wear it. Workers, representatives from deploying companies, and researchers consistently cited comfort as a barrier to worker use of wearables. For example, workers we spoke with said that exoskeletons can sometimes be hot and uncomfortable, particularly during summer months and periods of high humidity. Wearables also need to fit a wide range of body types, and many workers, particularly women, have cited poor fit, particularly around the chest and hips, as the reason for discontinuing voluntary use.

Convenience. The accessibility of wearables and the convenience of incorporating them into existing workflows arose as an overarching challenge for workers. We found in our conversations with workers and representatives from deploying companies that workers prefer to use wearables that are easy to access, quick to put on and take off, do not impede the fluidity of their motion when performing routine work, pose minimal snag risks, and are not likely to damage the company's product. For example, Department of Defense representatives who conducted an initial deployment of arm-support exoskeletons at shipyards reported concerns with convenience as one reason for discontinuing use. Shipyard workers generally only needed the exoskeleton for short-term, highly specific tasks and found that the benefit from wearing the exoskeleton did not exceed the burdens of carrying the exoskeleton the long distance between the lockers and shipboard work areas or of wearing the exoskeleton during jobs that didn't require its support.

3.2 Challenges raised by deploying company representatives

Identifying appropriate jobs. Workers are more likely to use wearables appropriately matched to their job. However, identifying appropriate jobs for wearables is not always straightforward. Representatives from multiple deploying companies said that identifying jobs that would most benefit from exoskeleton use often involved considerable trial and error. For example, arm-support exoskeletons may generally match well for overhead work, but only if a worker spends the majority of their time on that job in an overhead position and not moving back and forth between positions (see fig. 4). Similarly, ergonomic sensors may be designed to be worn in an upright position and may not be appropriate for workers who spend significant times in alternative positions, such as lying on their back.

Figure 4: Illustration of workers in an automotive manufacturing facility wearing arm-support exoskeletons

Figure 4: Illustration of workers in an automotive manufacturing facility wearing arm-support exoskeletons

Source: GAO (illustration). | GAO-25-107213

Identifying appropriate controls. Wearables may not be the most effective control in certain circumstances (see 1.2). For example, in a warehouse setting that requires employees to repetitively bend at the hips, a lift table might be a more effective intervention than a back-support exoskeleton because the lift table reduces the need for the worker to lift rather than providing support for lifting. In contrast, a common use case for arm-support exoskeletons in automotive manufacturing is underbody work—working on the underside of a vehicle—which cannot be easily eliminated due to the configuration of production lines. Likewise, data from ergonomic sensors, as noted above, could potentially identify job processes or environmental factors that increase risky postures. With this information, an ergonomist or health and safety professional can implement changes to the workspace through engineering controls, such as redesigning a workstation, that might reduce risk.

Limited efficacy data. A lack of data on injury reductions from publicly available studies, as discussed above, can make it difficult for companies to justify deployments and predict the likelihood of success when deploying wearables. Representatives we spoke to from companies deploying wearables discussed the need to justify the company's use of wearables. Limited efficacy data available for wearables, as discussed in chapter 2, can make it challenging for decision makers to decide if wearables are a cost-effective safety solution. For example, representatives from some deploying companies we spoke to did not feel that ergonomic sensors provided enough benefit on their own to justify the cost of deployment, in part due to limited efficacy data.

3.3 Data challenges

Data ownership. Multiple stakeholders raised concerns about the ownership of data collected from the use of wearables. For example, a representative from one deploying company we spoke to expressed concerns about data ownership and said it was unclear whether the data collected belong to the wearables manufacturer or to the deploying company as proprietary information. Additionally, officials from NIOSH said that there is an open question regarding worker access to and ownership of the data.

Data privacy. The data that some wearables collect and store also raise privacy and security concerns.[25] As we discussed in our previously issued Science & Tech Spotlight report, data on worker physiology and movements captured by monitoring devices such as ergonomic sensors can raise privacy concerns.[26] For example, workers surveyed as part of a wearables pilot test cited concerns about being tracked, and stakeholders we spoke to had similar comments. We also discussed in our spotlight that data stored on wearables may be vulnerable to hackers and therefore raise data security concerns. Stakeholders told us that larger companies may be better equipped to handle this challenge than small- or medium-sized ones.

3.4 Potential future challenges

Evolving market. The wearables market is evolving faster than wearables assessment and deployment in warehousing and manufacturing facilities. Companies interested in deploying wearables need time to research, procure, test, approve, and then deploy the technology. As a result, wearables manufacturers may develop a new generation of their device before a deploying company has finalized the implementation protocols for the generation they are working to roll out. This increases the risk of device obsolescence. For example, a representative from one deploying company said that the first exoskeleton system they deployed in

[25]We also found that privacy was the concern most frequently raised by stakeholders regarding digital surveillance of workers including wearable technology as well as other tools. See GAO, *Digital Surveillance of Workers: Tools, Uses, and Stakeholder Perspectives,* GAO-24-107639 (Washington, D.C.: Aug. 28, 2024).

[26]GAO-24-107303.

2019 had a new model released less than a year later, and the company needed to restart its assessment and approval process for the new model.

Worker burdens. More frequent deployment of wearables in manufacturing and warehousing workplaces may raise additional concerns in the future, such as misplaced safety burdens and punitive use. Some stakeholders expressed concerns about wearables placing the burden of safety on the worker rather than on the company to improve the safety of the workplace. According to NIOSH officials, there is a risk that some companies may use wearables to focus on changing worker behavior for non-safety goals rather than on providing a safer work environment. While we found no evidence of current punitive uses and union representatives said no issues related to wearables had been reported to them, they expressed concerns about the potential for punitive use of data collected by wearables. For example, workers may be reprimanded for performing too many risky bends in a shift. Finally, stakeholders also expressed concerns about companies exploiting wearables to drive additional worker productivity, which may reduce any safety benefits. For example, if a worker feels less fatigued due to using wearables, they may feel pressured to accomplish more of a task in a given time period, increasing risk for musculoskeletal injury due to repetitive motion.

4 While Stakeholders Resolve Deployment Challenges, Policy Changes May Not Be Useful

Stakeholders told us that more time is needed to resolve various challenges related to wearables in the industrial workplace before policy changes, such as additional standards and regulations, may be useful. For example, national consensus committees are currently developing new consensus standards to address concerns such as safe design and manufacture, risk management, and ergonomics. Stakeholders suggested that they could continue current activities, such as exploring deployment of wearables and documenting findings, allowing the market to develop and identify the best technologies, and gathering and responding to worker feedback.

As stakeholders continue their existing activities, more information may become available about challenges, concerns, and other issues that arise when deploying wearables. In addition, more time could yield additional data on the extent to which wearables improve worker safety or reduce workplace injuries. This improved understanding could help inform future decisions made by deploying companies, worker organizations, manufacturers, and federal agencies. One potential disadvantage of continuing current activities without policy intervention, however, is that it could allow wearables to enter the marketplace without safeguards to prevent data abuse or potential future punitive use.

Below, we identify and describe selected ongoing activities that different stakeholders are undertaking. According to our discussions with stakeholders, these activities may address many of the challenges outlined in chapter 3.

Table 2: Selected activities stakeholders are undertaking, which may address deployment challenges

Stakeholder group	Selected activities to continue	Challenges addressed
Deploying companies	Considering hierarchy of controls to mitigate work hazards with controls that are more effective than personal protective equipment (PPE), such as elimination, substitution, or engineering controls. Wearables may be worth using when a more effective control is not possible, which may help ensure the wearable is appropriate to the task.	Identifying appropriate jobs; Identifying appropriate controls
Deploying companies	Gathering feedback from workers on concerns including comfort, ease of use, appropriateness to the task, data ownership, and policies on voluntary usage.	Comfort; Convenience; Identifying appropriate jobs
Deploying companies	Evaluating safety culture. Companies that prioritize safety over productivity will likely have more successful deployment of wearables.	Worker burdens
Deploying companies	Defining goals of successful deployment and developing implementation protocols. Depending on how success is defined, companies may be able to evaluate effectiveness in worker safety improvement, injuries and discomfort reduction, and worker acceptance.	Identifying appropriate jobs; Limited efficacy data; Evolving market
Worker organizations	Gathering worker feedback as companies deploy wearables. Doing so may help ensure that wearables are comfortable and convenient and deter the punitive use of wearables by deploying companies.	Comfort; Convenience; Worker burdens
Worker organizations	Monitoring company deployment of wearables may ensure that appropriate hazard controls are employed and prevent infringements on worker rights and protections.	Identifying appropriate controls; Worker burdens
Wearables manufacturers	Gathering and providing additional data on accuracy and efficacy of devices to help deploying companies make decisions through lab- and field-based evaluations and address the current lack of data on injury reduction.	Identifying appropriate jobs; Limited efficacy data
Wearables manufacturers	Evaluating market trends to respond to company and worker feedback and refining products as appropriate, such as ensuring that wearables are comfortable, easy to use, and have data security.	Evolving market; Comfort; Convenience; Data privacy;
Academia	Partnering with wearables manufacturers and deploying companies to conduct pilot testing and collect data on efficacy of wearables.	Identifying appropriate jobs; Limited efficacy data
Academia	Expanding wearables applications beyond musculoskeletal injury prevention, such as data-processing methods for ergonomic sensors to monitor hazards related to slips, trips, and falls.	Identifying appropriate jobs; Identifying appropriate controls; Evolving market
Federal agencies	Funding research on accuracy and efficacy to help increase data on wearables and how they could be deployed in the workplace (National Institute for Occupational Safety and Health).	Limited efficacy data

Stakeholder group	Selected activities to continue	Challenges addressed
Federal agencies	Enforcing workplace health and safety laws may help identify problems related to deployments, such as if a company is deploying wearables as a substitute for ensuring a safe work environment (Occupational Safety and Health Administration).	Worker burdens

Source: GAO. | GAO-25-107213

5 Agency and Stakeholder Comments

We provided a draft of this report to the Departments of Health and Human Services, Labor, and Defense with a request for technical comments. We incorporated agency comments into this report as appropriate.

We also provided a copy of the draft report for review and comment to stakeholders representing some of the groups identified in our discussion of ongoing activities: deploying companies, wearables manufacturers, and academic researchers. We incorporated stakeholder comments as appropriate.

As agreed with your office, unless you publicly announce the contents of this report earlier, we plan no further distribution until 30 days from the report day. At that time, we will send copies of this report to the appropriate congressional committees, the relevant federal agencies, and other interested parties. This report will be available at no charge on the GAO website at https://www.gao.gov.

If you or your staff members have any questions about this report, please contact Karen L. Howard at (202) 512-6888 or HowardK@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made key contributions to this report are listed in appendix II.

Sincerely,

Karen L. Howard

Karen L. Howard, PhD
Director,
Science, Technology Assessment, and Analytics

Appendix I: Objectives, Scope, and Methodology

Objectives

We describe our scope and methodology for addressing the three objectives outlined below:

1. To what extent do select wearable technologies affect worker safety?

2. What challenges exist for deployment of wearable technologies in the workplace?

3. What activities, if any, may help address these challenges?

To address all research objectives, we conducted a literature search and reviewed key reports, peer-reviewed articles, and literature from nonprofits and wearables manufacturers. In addition, we interviewed a variety of stakeholders including federal agency officials; academic researchers; unions; nonprofits; and private companies, including those that deploy or have deployed wearables and those that manufacture wearables. We also conducted two site visits to private companies deploying wearables to speak with occupational health and safety personnel and workers who use wearables and attended the Applied Ergonomics Society's 2024 conference.

Scope

The scope of our assessment included manufacturing and warehousing workplaces and two wearables of interest for deployment in those workplaces to address musculoskeletal injuries—namely, exoskeletons and ergonomic sensors. We assessed the status of the field of wearables as a whole, but we did not assess any particular brand of specific exoskeletons or ergonomic sensors.

Methodology

<u>Literature search and review</u>

For all objectives, we reviewed relevant literature identified by agency officials, stakeholders, and a literature search conducted by a GAO research librarian. The librarian searched a variety of databases, including ProQuest and SCOPUS. We narrowed our search to articles published from 2019 through February 2024 to capture recent developments and uses of wearables as well as any quantitative metrics available on the effect of wearables on worker safety. Results of these searches could include scholarly or peer-reviewed material; government reports; trade or industry papers; and association, nonprofit, and think tank publications.

The team used a two-tiered process to select the articles from the literature search that were most relevant to our objectives for further review. After review by two team members, the team identified and requested full texts of 24 studies which focused on in-scope technology (i.e., exoskeletons and ergonomic sensors), and either 1) were validation studies measuring the performance of the technology, such as accuracy, in the lab or field or 2) were verification studies measuring the impact of the technology on worker safety in the lab or field. Two team members then reviewed the full text of the resulting studies to determine relevance. A study was deemed relevant if it dealt with manufacturing, warehousing, or construction industries and focused on quantitative measures on the effect of the technology on worker safety.[27] Eight of the 24 studies were determined to be relevant to field studies using these criteria.

Additionally, the team completed a higher-level analysis for eight published studies on laboratory-based exoskeleton research identified from the literature search results. These studies did not meet criteria of having quantitative metrics on safety but did provide details on the laboratory work for determining muscle strain reduction from exoskeletons.

Interviews and site visits

We interviewed a selection of key stakeholders with experience and perspectives on the above objectives. We identified these stakeholders from a variety of sources including our review of literature, interviews, and prior GAO work:

- Officials from the Departments of Health and Human Services (National Institute for Occupational Safety and Health), Labor (Occupational Safety and Health Administration and Bureau of Labor Statistics), and Defense (Naval Sea Systems Command)
- Academic researchers
- Representatives from wearables manufacturing companies
- Representatives from companies deploying, or who have deployed, wearables
- Representatives from worker organizations, including unions
- Representatives from a nonprofit organization focused on workplace safety, funded in part by industry donors

Because this is a purposeful selection of the stakeholders involved in developing and using wearables, the results of our interviews are illustrative and represent important perspectives but are not generalizable.

We also went on two site visits to companies deploying wearables who agreed to host our team, and we attended the Applied Ergonomics Society 2024 conference. During the site visits, we spoke to occupational health and safety professionals responsible for overseeing the deployment procedures and use of the wearables and to workers who are currently volunteering to use wearables or have used wearables in the past. During one site visit, we were also able to observe how workers used exoskeletons during their day-to-day work tasks. At the conference, we heard presentations from occupational health and safety professionals and academics, interfaced with several wearables manufacturers, and tried on some wearables.

Ongoing activities

After careful consideration of documentary and testimonial evidence, we determined that it would not be useful to identify policy

[27]While construction was not in scope for this work, some studies for construction field work were included if there was substantive information about ergonomic sensors or exoskeletons and if the conclusions were applicable beyond the construction sector.

options because current activities, if continued, may address the challenges we identified. We therefore describe several ongoing activities for each relevant stakeholder group to consider continuing in lieu of providing policy options. The discussion of ongoing activities is neither a recommendation to federal agencies nor a matter for congressional consideration.

We conducted our work from January 2024 through December 2024 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

Appendix II: GAO Contact and Staff Acknowledgments

GAO contact

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