

The Ethics of Mandatory Exoskeleton Use in Commercial and Industrial Settings

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Abstract—Research shows exoskeletons can reduce muscle activity and decrease the risk of injury for workers. Exoskeletons, therefore, are becoming more prevalent in industrial workplaces, and their use in some circumstances has already been mandated. It is probable that additional employers will mandate the use of exoskeletons as a means of mitigating injuries to their employees. This presents ethical concerns because employers hold power over the employees' wages and employment. Some employees who are required to wear exoskeletons may not be able to, while others may not wish to. How should workers' privacy and preferences be weighted? Should employees be prohibited from jobs that use exoskeletons if the exoskeletons do not fit them or if they do not wish to disclose their body's measurements? Should companies using exoskeletons be permitted to require workers to perform additional work with an exoskeleton? In this paper, we examine these and other ethical considerations related to mandatory exoskeleton use through the Six Pillars of Character framework of the Josephson Institute of Ethics (2002) and the Universal Moral Values for Corporate Codes of Ethics framework by Schwartz (2005). We provide a discussion of possible solutions following ethical tenets, including executing pilot studies before mandatory use policies, offering several self-adjustable models of exoskeletons, and allowing existing workers to transfer jobs if they are ill at ease with new exoskeleton policies. The best course of action may depend on specific individual circumstances.

Index Terms—Ethics; Exoskeletons; Manual Material Handling; Robotics

I. INTRODUCTION

EXOSKELETONS are wearable devices that augment strength and endurance. Research shows exoskeletons can reduce muscle activity by up to 60% during physical labor and decrease the risk of musculoskeletal injuries for workers [1]–[3]. The potential for reducing injuries or otherwise aiding workers is leading to the rapid adoption of exoskeletons: projections show exoskeleton use growing at a Compound Annual Growth Rate (CAGR) of 43%, increasing to a global market size of 5.7 billion USD by 2027 [4]. Of this, approximately 30% (1.7 billion USD) is in industrial settings [5]. Exoskeletons, therefore, are becoming more prevalent in industrial workplaces such as manufacturing, logistics, and warehousing [6], and their use has already been mandated in some circumstances¹ [7], [8]. It is probable that additional

employers will mandate the use of exoskeletons as a means of mitigating injuries to their employees. This presents several ethical concerns because exoskeletons are not like traditional tools used in industrial workplaces. For example, mandating that an employee use a drill does not pose an ethical problem so long as the employee receives proper safety training. However, mandating that all employees wear a special jacket that is two sizes too small for some people and causes bruising or high blood pressure in others, presents several ethical issues. While exoskeletons are different from this scenario, the same ethical issues that are present with the special jacket are present with the mandatory use of exoskeletons.

This prompts the question of, what exactly are exoskeletons and how precisely do they differ from existing tools used in industrial settings? Exoskeletons are mechanical devices that fit closely around the body and create forces on the body. They can either be active, and use power sources to supplement a person's motion, or passive, and compensate for the effects of gravity on a person or a tool through the use of springs. Some tool-holding or full-body exoskeletons extend all the way to the ground and can transfer forces there; these exoskeletons can offload some or all of the weight lifted by a user. Other exoskeletons do not extend to the ground, such as lower back and shoulder exoskeletons. These require the wearer to carry the full weight of the device and in almost all circumstances do not provide complete support or augmentation for the user's joints, so that the user still must exert themselves to move or perform tasks².

Power equipment such as forklifts, Personal Protective Equipment (PPE), and exoskeletons can all be used to protect the wearer and prevent injuries; however, exoskeletons differ from power equipment and PPE in several key ways. PPE provides an external barrier of protection between the wearer and environmental hazards, and if used properly, should mitigate the risk of injury from external hazards. Different hazards require various types of PPE to mitigate them, and the types of PPE are dependent on the specific job hazards that are likely to be encountered. Some examples of PPE include helmets, goggles, face masks, gloves, reflective vests, fire-proof clothing, and respirators. In nearly all situations, work can

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¹Toyota has mandated an arm exoskeleton for use in certain jobs that do overhead work, in all of their manufacturing plants. Prior to implementing this, they conducted extensive trials. We are not aware of any other examples of mandatory exoskeleton use at this time.

²For example, most passive back exoskeletons support between 15-45% of the torque required at the hip during freestyle lifting. A summary is in [9].

be done without the use of PPE; however, there is a significant increase in the risk of injury without it. Decades ago, many industries that now require the use of PPE to protect workers would have offered little in the way of safety equipment. This is true of many industries such as mining, construction, and manufacturing. Today, PPE is required to meet safety standards regulated by the government and, in most cases, employers are required to purchase and provide PPE to all employees when such protection is necessary during the course of work [10].

While most PPE protects workers from external hazards, exoskeletons for industrial use are designed to reduce internal musculoskeletal injuries. These internal injuries can occur from lifting objects, working in awkward (non-ergonomic) postures, or performing repetitive motions. It is possible to teach someone proper lifting techniques, but they may not actually use those techniques in practice [11]. Exoskeletons protect from internal injuries in a similar way to using a proper lifting form: they reduce some of the forces *within* the body that have the potential to cause injury.

Additionally, exoskeletons are distinct from PPE in that while there are stringent regulations for PPE, OSHA does not have specific regulations for exoskeletons themselves³, or even about safe manual material handling in general. Rather, OSHA has general guidelines for safe lifting and motion [12], [13]. Thus, significant leeway is possible in work environments, and with the current system, injuries still occur [14]. While exoskeletons show promise for reducing injuries relative to the current baseline, with the non-specific regulations currently in place, there exist opportunities for exploitative or unequal treatment of workers [15].

In addition to being distinct from PPE, exoskeletons are also distinct from external tools such as forklifts or hoists in several ways. Power equipment such as forklifts, overhead hoists, and, in some cases, robotic automation remove the worker from hazards—i.e., by making it so the worker does not have to do the manual work themselves. However, for smaller loads, abnormally-shaped objects, or manual tool holding tasks, it is not possible or practical to use power equipment. In these circumstances, individuals typically move materials or tools themselves, placing the strain on their bodies. It is in these circumstances that exoskeletons are frequently targeted for use.

Exoskeletons present a unique set of concerns related to their use and adoption; these concerns are different than concerns with the current tools used in manual material handling. With exoskeletons, first, the wearer typically must still supply a large amount of the force to manipulate an object being lifted or a tool being held: this is not true of a forklift or powered hoist. Exoskeletons do not typically interact with a load directly, but just provide torques to a subset of the wearer's joints, e.g. the hip or shoulder. Second, in most cases exoskeletons supply forces to the body that would not otherwise be there: in creating torques, the exoskeleton must push against the body in multiple places. Third, exoskeletons are extremely close-fitting to the

body, and usually follow the wearer's kinematics. Generally, an exoskeleton will not work properly unless it is appropriately fit to a wearer's body.

The introduction of exoskeletons into workplace settings could also be compared to the introduction of powered hand tools such as jackhammers or saws in industrial environments such as manufacturing and construction, where previously unpowered tools were solely used. Prior to the introduction of powered tools, digging with a pick axe or cutting with a saw needed to be done purely with the operator's energy. The introduction of powered tools allowed the jobs to be done much more easily, with less strain on the body due to the shorter amount of time required to complete the task (i.e., a person needs much less time and energy to complete a cut with a powered chainsaw as compared to an unpowered hand saw), and with likely less strain on the body due to the tool doing the cutting work [16]. With exoskeletons, in almost all circumstances the person still is completing the tasks in the same amount of time, but the exoskeleton reduces forces on the body in targeted areas. Thus, while power tools present obvious gains in efficiency due to the shorter overall task time, most exoskeletons are solely intended to protect the wearer and do not nominally lead to increased productivity. Unfortunately, powered tools trade one set of potential injuries (overuse and task-specific dystonia [17]) for another, including those from vibration, possible strains due to lifting a heavy tool, and a greater risk of accidental injury [18]–[20]. These risks and potential secondary injuries are accepted trade-offs for the increase in productivity. Exoskeletons too may increase the risk of secondary injuries, and apply new forces to the body, but these are not as well understood since exoskeletons are an emerging technology. With power tools there is a general understanding of possible secondary injuries with recommendations and guidance in place to aid in prevention [20]. With time, similar guidance may be issued for exoskeletons; however, this will require more observation and research. Overall, the use of exoskeletons in a workplace is somewhat more similar to the use of PPE, where the purpose is to protect a user from harm instead of to increase productivity. Even so, additional lessons can be learned in comparing the introduction of exoskeletons to the introduction of power tools in workplaces.

In the same way that required PPE protects workers from harmful environments, mandating the use of exoskeletons could protect workers from harmful situations such as repetitive tasks and heavy lifting. However, compulsory exoskeleton use raises a number of ethical questions. Not all workers who are in a certain job where exoskeletons are mandated will be able to fit into them or be able to wear them for other reasons. Additionally, there are a number of valid reasons why an employee may not want to wear an exoskeleton that relate to privacy, possible injury risk, or psychological factors. In all of these cases, the heart of the ethical debate that surrounds

³ There are regulations for exoskeletons and devices used in medical rehabilitation, but those are not relevant in industrial environments.

companies mandating the use of exoskeletons for their workers is the power imbalance between employer and employee. We envision two different scenarios where this comes into play: (1), if exoskeletons are newly introduced into a job where people have been working without them thus far; and (2), if exoskeletons are already in use by existing employees and only new employees need to be fitted and trained in their use. In cases when exoskeletons are newly-introduced, compulsory use of exoskeletons as a condition of employment requires the employee to make the decision between keeping their job or protesting and risking losing it [21]. For many in this position, there is little choice, as average incomes for manual laborers are between \$25,870 and \$33,430 depending on the specific industry [14]. Because of the non-specialized nature of most manual labor, workers lack leverage in negotiations [21], [22] and in many instances can, and do, find themselves quickly replaced. It is this power inequality that leads to the ethical conflicts examined in the rest of this paper for both existing and new employees.

Despite the anticipated increase in exoskeleton adoption, there has been only sparse work on the ethics of exoskeletons related to the issue of mandatory use in industrial and commercial settings [23]–[25]. In his 2015 paper, Greenbaum focuses on ethical concerns regarding military and sports exoskeletons [24]. Greenbaum also states that there is scant research into the ethics and social impacts of exoskeleton adoption. Kapeller et al. [23] conducted a multi-year survey of experts and provides a breadth of ethical and legal implications; however, they focus on powered exoskeletons or “wearable robots.” These powered devices dominate the rehabilitation space whereas powered industrial exoskeletons are in their infancy with prices that put them out of reach for most companies⁴. Maurice et al. [25] surveyed workers and non-workers on exoskeleton use, finding an overall positive outlook on exoskeleton use with workers’ concerns focusing on comfort and freedom to choose when to use an exoskeleton. Also, a study conducted by the European Union discusses the legal and ethical issues around self-driving cars, medical robotics, and robotic prostheses, classifying exoskeletons with the latter [27]. While the authors do an in-depth review of the ethical and social implications of adopting robotic prostheses, they primarily address brain-machine interface technology and do not address the ethics of exoskeleton use in industrial or commercial contexts. Felzmann et al. [28] and Nussbaum et al. [6] contend that the field of wearable devices would benefit from a more in-depth review of the ethics of exoskeleton use.

Thus, this paper addresses gaps in the current literature by focusing on the ethics of mandatory exoskeleton use in commercial and industrial settings: situations where an employee is compelled by their employer to wear an exoskeleton as a condition of their job. It does so by exploring the ethical issues through the frameworks of the Six Pillars of Character by the Josephson Institute of Ethics [29] and the

Universal Moral Values for Corporate Codes of Ethics identified by Schwartz [30], as these consider a general set of ethical standards that are applicable to corporations. Both of these include the same six tenets: Trustworthiness, Respect, Responsibility, Fairness, Caring, and Citizenship. With respect to mandatory exoskeleton use, the tenets of Trustworthiness, Respect, Fairness, and Caring are applicable and deciding on the best course of action frequently includes adjudicating between them. Trustworthiness includes safeguarding confidential information, among other things. Respect includes considering others’ perspectives, allowing people to make decisions on their own, and providing necessary information to them. Fairness includes avoiding prejudice and providing equitable treatment. Caring includes looking out for the welfare of others and avoiding unnecessary harm. Responsibility and Citizenship are not relevant since Responsibility pertains to accountability and the pursuit of excellence, and Citizenship encompasses following the law and contributing to society. Responsibility will apply regardless of exoskeleton use, and currently there are no laws about industrial exoskeletons. By using this framework, different conflicting ideas can be compared against each other, and decisions about exoskeleton use can be guided according to established values.

The remainder of this paper is organized around several topic areas. These are: Undesired Effects on the Body, Fit and Sizing, Overuse and Overwork, and Additional Concerns.

With emerging technologies, there are always unforeseen ethical issues around adoption. In the case of mandatory exoskeleton use in industrial settings, there are possibilities to mitigate against ethical concerns preemptively. It is important to understand the issues listed above before exoskeleton use in commercial and industrial settings becomes widespread. In the remainder of the paper, we discuss these issues in more detail. Our objective is to enumerate the possible ethical issues that can arise from mandatory exoskeleton use, evaluate them through the lens of the six ethical tenets, and present possible solutions to the issues. A summary of the ethics tenets, how they can be applied to exoskeleton use, and some possible solutions explored in this paper is shown in Fig. 1.

II. UNDESIRE EFFECTS ON THE BODY

Unlike the protection provided by PPE, which is designed to impose a barrier or restriction to limit an individual’s exposure to external hazards⁵, exoskeletons seek to decrease the physical strain placed on one or more parts of an individual’s body. While full body exoskeletons (e.g. [31], [32], and Fig. 2(a)-(b)) transfer external loads to the ground, these are relatively less common than joint-specific exoskeletons that provide support for only one joint or part of the body such as a shoulder (e.g. Fig. 2(c)-(d)) or lower back (e.g. Fig. 2(e)-(g)). The other parts of the body that are not supported by the exoskeleton may receive the loads they felt previously, may support additional forces due to the weight of the exoskeleton, or may support even

⁴ Full body powered exoskeletons that can lift and carry up to 90 kg can cost as much as \$100,000 per year [26].

⁵ External hazards are defined in the OSHA 1910 standards and include physical, chemical, biological, auditory, and electrical dangers.

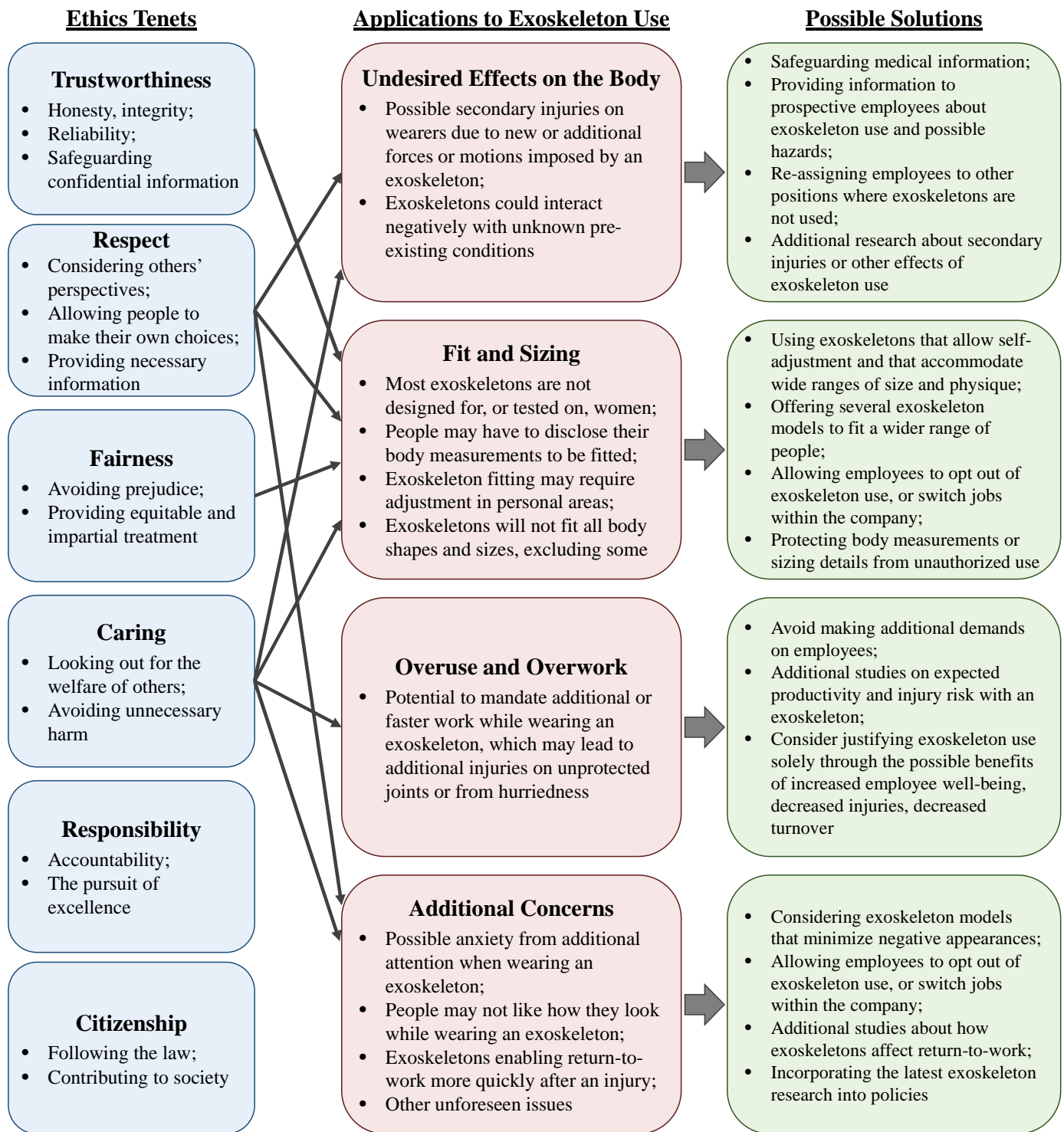


Fig. 1. Summary of the Ethical Tenets considered in this paper, how they apply to exoskeletons, and possible solutions. Note that the tenets of Responsibility and Citizenship are not currently applicable to exoskeletons.

higher forces due to the exoskeleton transferring forces from one part of the body to another. For example, most passive back exoskeletons only extend from the torso to the thighs [33]–[35], and reduce the activity of the back muscles. The wearer's arms are not supported and sustain the loads they did even without an exoskeleton. The wearer's feet must support the additional weight of the exoskeleton in addition to the original load. In many cases, the exoskeleton reduces the activity in the leg

muscles [36], [37], but in some cases, the exoskeleton actually can increase the muscle activity in the legs due to the exoskeleton's method of load transfer [38]–[40]. Thus, while exoskeletons can reduce the impact of lifting on specific joints on the wearer, they do not entirely protect a user from the hazards of lifting and may increase forces on certain joints [6], potentially causing secondary injuries such as joint pain [41].

Similarly, exoskeletons may have other unwanted impacts on

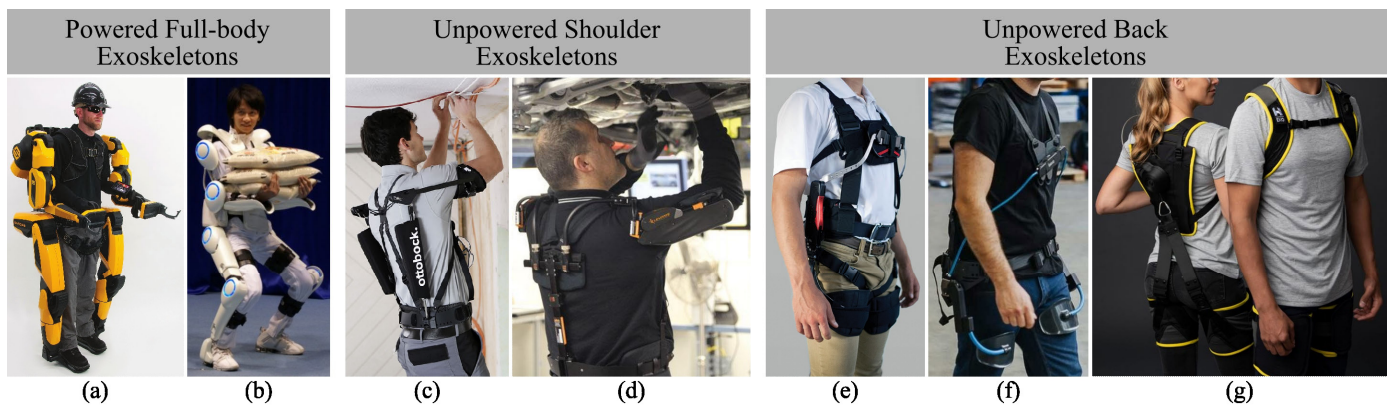


Fig. 2. Some examples of commercially available exoskeletons. (a) Sarcos Guardian XO full-body exoskeleton; (b) Cyberdyne HAL-5 exoskeleton; (c) Ottobock Paexo Shoulder exoskeleton; (d) Levitate Airframe shoulder exoskeleton; (e) SuitX (owned by Ottobock) backX exoskeleton; (f) Laevo V2.5 exoskeleton; (g) HeroWear Apex exosuit.

parts of the body. Exoskeletons necessarily apply pressure to the skin during their operation. Especially if individuals have sensitive skin or are elderly, this may lead to bruising or skin damage [41]–[43]. Even in young people, bruising has been reported to occur at pressure points on an exoskeleton such as chest plates [38], [44]. In addition, exoskeletons can potentially cause chafing [45], [46]; overheating [46]; can lead to restrictions on movement [3], [47]–[49]; or could increase the probability of a fall due to instability from added mass or erroneous motion from a powered exoskeleton [44], [50]. Secondary injuries from robotic gait trainers (non-portable exoskeletons) have been documented in medical research, where strict rules govern reporting in medical device trials. These injuries include joint and muscle pain, skin abrasions and lesions, bruising, high or low blood pressure, and even a tibia fracture [41]. These injuries could potentially also be caused by portable exoskeletons.

A primary reason for wearing an exoskeleton is to reduce the user's risk of injury while performing a given task (lifting, tool holding, etc.). Some musculoskeletal injuries due to these tasks are very costly to both the user and employer; two of the most common are shoulder and back injuries, costing an estimated \$46,205 USD and \$36,882 USD per injury, respectively⁶ [51]. For comparison, unpowered exoskeletons can cost between \$2,500 to more than \$7,000 USD depending on the part of the body supported and the capability of the exoskeleton [52]–[55].⁷ It is possible that the use of an exoskeleton comes with the consequence of increasing the risk of a secondary injury. This trade-off may be worthwhile if the secondary injury is a lesser injury. That is to say, the injury is significantly easier to treat, (e.g. does not require surgery), costs less to treat, or is less likely to impact the user over time (e.g. is less painful or does not impact their daily lives). However, if a secondary injury is a direct result of wearing the exoskeleton, several ethical issues arise [41], [45].

First, it may be unethical for the management to make the

decision on exoskeleton use on behalf of an employee. This is particularly relevant if exoskeletons are newly introduced into a workplace. In this case, some employees may have medical conditions where increased forces, pressures, or heat burden could result in injuries. There are also negative implications for privacy if employees need to disclose pre-injuries or medical conditions that they otherwise would not have had to disclose. Thus, there is the potential ethical issue of management trading one injury risk profile for another without an employee's consent. Mandating exoskeletons would oppose the tenet of Respect—allowing employees to make their own decisions. However, if exoskeletons are introduced to decrease the rates of known possible injuries for that job (i.e., Caring for the employees), there is a tension between Respect and Caring. In order to mandate exoskeletons, the management should have a large amount of data on the possible secondary injuries caused by those exoskeletons, including when people wear them who have medical conditions or who are otherwise extra susceptible to secondary injuries. Unless this data is obtained (e.g. through controlled studies or trials where employees can opt in), it is not possible to know how the risks of secondary injuries from an exoskeleton compare with the known job risks. If medical information must be disclosed while evaluating if an exoskeleton is acceptable for an employee's use, the disclosed medical information must be safeguarded even if confidentiality is not legally required (Trustworthiness tenet).

If using an exoskeleton is a precondition of employment for a newly-hired employee, and the employee is the decision maker, they need enough information to make a properly informed decision. This information should consist of the specific biomechanical risks that a job entails, an exoskeleton's potential hazards and how they would align with various medical conditions, who will be responsible if an injury occurs (with or without an exoskeleton), and whether it is possible to opt out of using an exoskeleton in the future. Providing this information satisfies the tenet of Respect. Additionally, policies

⁶ Approximately half of each of these costs are medical expenses, and about half are costs for workers' compensation indemnity (i.e. payments to the employee, including for paid time off).

⁷ Current unpowered exoskeletons designed to protect workers' shoulders range in price from \$4,000 to \$7,000 [52], [53], and unpowered back assist exoskeletons range from \$2,500 to \$6,700 [54], [55]. One full body powered exoskeleton (Fig. 2(a)) can cost as much as \$100,000 per year [26].

that are Fair would allow a new employee to be reassigned to a different position if it turns out that they have an unknown-to-them medical condition that prevents them from using an exoskeleton.

Employees may not wish to wear something at all if it causes them even minor inconvenience [25], [46]. An analogous situation is that people sometimes do not wear PPE, even though it is proven to reduce injuries [56], [57]. Thus, the tenet of Caring would suggest that mandating exoskeleton use may be preferable to optional use, as long as the injury profiles and risks of a job while using exoskeletons are substantially less than the risks of doing the job without them, and as long as provisions are made for individuals who cannot wear exoskeletons.

Finally, in terms of undesired effects on a person's body, it is also useful to compare exoskeletons to power tools. Many power tools, such as jackhammers, chainsaws, and impact drivers, improve productivity by making previously difficult and time consuming jobs more efficient. They do this at the cost of introducing vibration related hazards to workers which can lead to secondary injuries such as nerve damage in the hands and arms [18]–[20]. For nearly half a century after the introduction of jackhammers, vibration syndrome was little known and even less accepted as an issue with their use, leading to permanent injuries often called “white finger disease” [58]. It would take nearly half a century more for the introduction of recommendations to prevent hand-arm vibration syndrome in the 1970s and 1980s [20] and regulations in the mid 2000s [59]. From this example, we can expect that regulations for exoskeletons might arise if the risk of secondary injuries is shown to be substantial. Even in the absence of regulations, employers have an ethical obligation to provide a safe working environment. Since exoskeletons are a new technology that may have unintended consequences, it is important to research their effects and potential for secondary injuries. Ideally, this would be done before widespread adoption, so employers and employees could make informed decisions.

Additionally, when analyzing unwanted impacts on a wearer, it is informative to compare exoskeletons to the use of natural rubber latex (NRL) gloves, a form of PPE which causes new, permanent, allergies in 1-2.5% of healthcare workers each year [60]–[62] and has been the cause of workers' compensation claims [63]. Alternative glove materials do not cause allergies, and with workplace modifications, healthcare professionals can continue in their jobs [61], [62]. As Bernstein noted, workplaces have a responsibility under the Americans with Disabilities Act to make reasonable accommodations for impaired employees [64]. Regulations have been introduced in Germany to only allow low-allergen NRL gloves, which led to a decrease in allergic reactions [61], but these have not been adopted by all countries. With exoskeletons, there could potentially be workers' compensation claims if an exoskeleton was mandated and caused secondary injuries such as skin abrasion. It is less clear what accommodations would look like in this case: they could potentially include using a different exoskeleton model; or not using any exoskeleton at all, although potentially a workplace would have to be modified if

it was optimized for use with exoskeleton-wearing employees. In general, the risk and injury trade-offs for an exoskeleton will likely be particular to each individual situation.

III. FIT AND SIZING

Exoskeletons often require precise alignment and fit to transfer energy from the exoskeleton to the user effectively and safely—most exoskeletons must be very close-fitting to work properly [43], [65]. Achieving this requires either measuring several of the wearer's body dimensions, or, more commonly, adjusting straps to fit snugly around their body while the worker is wearing the exoskeleton. For example, a lift-assist exoskeleton that attaches to the wearer at the shoulders, waist, and thighs may require measurements or adjustments at all three locations (e.g. Fig. 2(a)-(b) and (e)-(g)).

This is unlike PPE which does not rely on such precise fits to perform its primary function. PPE typically comes in generic sizes (e.g. small, medium, large, etc.), specific sizes (as in the case of steel-toed boots), or is designed to fit a broader range of individuals such as a one-size-fits-most approach as might be found with reflective vests or protective eyewear. In the latter cases, less precise sizing does not impair PPE's functionality. Because exoskeletons are designed to work in conjunction with the wearer's body, a one-size-fits-most or an overly large design could significantly impair the assistance provided by an exoskeleton [6], [66] and potentially increase the injury risk due to misalignment between the exoskeleton and the wearer's joints [65]. Misalignment of forces on a joint can result in pain or injury to the joint [41], [50].

Some exoskeletons can be self-adjusted to obtain a precise fit, but with others it may not be possible for the wearer to fit themselves or even reach the adjustments while wearing the exoskeleton [42]. If self-adjustment is not possible, a wearer must either disclose their body dimensions prior to being fit for the exoskeleton or be in very close proximity to the fitter while the proper adjustments are made [67]. In the case of leg and back exoskeletons, the areas that might require adjustment may be personal in nature—thigh diameter, chest size, and waist size. This has the potential to make some wearers uncomfortable or possibly feel violated. This can be particularly true if the individual doing the fitting is a stranger, a representative from the exoskeleton company, or perhaps a manager. Mandating that individuals go through a fitting procedure or disclose their body dimensions may be unethical, as it conflicts with Respect. In situations where employees cannot adjust the fit themselves, they should be able to opt out of the exoskeleton use, or an alternate exoskeleton should be provided that allows them to self-fit.

When personal sizing details are recorded for fitting or to determine if a person will fit an exoskeleton at all, the potential for discrimination exists in that personal dimensions could be used illegitimately to make inferences about employee health and well-being. In an extreme scenario, the unethical use of this information could be used in a decision to lay off an employee. For this reason, to follow the tenets of Trustworthiness and Caring, body measurements and exact sizing details should be treated as personally identifiable information (PII) and policies should be put in place prior to collecting such information to prevent its

unauthorized use. Possible measures for protecting PII include obfuscating the employee's identity by disconnecting their name from their sizing information.

It is true that some uniforms, such as dress uniforms, are tailored specifically to the wearer; however, the uniform fit can vary for different body types to maximize the wearer's appearance. When a uniform does not fit properly, the result is a negative impact on the appearance of the wearer. This fitting is frequently done by a tailor who is selected by the wearer. Exoskeletons, in comparison, are required to fit to the wearer's joints, not just their body form. At the present time, there are no dedicated professions for adjusting exoskeletons (as in the case of a tailor) and so exoskeletons may be adjusted by supervisors or technical support personnel from the exoskeleton manufacturer; these people cannot be selected by the exoskeleton wearer. When an exoskeleton does not fit properly, the consequences can range from a lack of protection (similar to when PPE does not fit properly) to the exoskeleton causing secondary injuries. Distinct from both uniforms and PPE, exoskeletons must work with the wearer's body joints, not just fit over top of their body.

Nearly all exoskeletons are available with discrete sizes or adjustability built into their design [31], [33], and accommodate a range of body sizes and types. However, virtually all exoskeletons will not fit all individuals, especially for those who are on the extremes of sizing, either height or diameter [68]. This is especially an issue with the exoskeleton industry being in its infancy, so wide ranges of sizes have not yet been created as they have been for PPE. How an employer handles the situation where an employee cannot properly fit into an exoskeleton creates several ethical challenges related to Fairness. Those who are outside the size range may find themselves excluded from the use of the exoskeleton [3], and possibly excluded from jobs requiring their use. At the very least, they would not receive the benefits of wearing an exoskeleton, resulting in a form of discrimination based on the individual's body size. One possible solution is for exoskeleton designers to increase the size options provided, but this will take development time and is not something that a manager can control. Managers could select exoskeleton models that accommodate wide ranges of sizes, in order to maximize Fairness. Another solution is to make the ability to wear an exoskeleton (and thus be within specific height and weight ranges) part of the job requirement. This still creates ethical issues in situations where exoskeletons are newly-introduced into existing jobs, however. In this case, employees should be able to switch jobs within the company in order to maintain Fairness.

Like exoskeletons, heavy power tools are not a one-size-fits-all device. Jackhammers and chainsaws are available in multiple sizes to align not only with the task but also the capabilities of the operator. A heavy jackhammer requires an operator of sufficient strength to wield the tool properly. For exoskeletons, the size and support must be matched to the individual and the tasks they are performing. Proper fit allows the exoskeleton to function with the wearer while properly aligning the exoskeleton to the task is necessary to provide proper support to the wearer. Exoskeletons are at a stage similar to the very beginnings of powered tool use, where they are not present in most industries but their use is rapidly expanding. Having the option to fit all employees with

exoskeletons that can provide protection is fair and equitable, allowing existing workers to continue their jobs.

While fit and sizing are important for everyone, one omission in exoskeleton sizing and fit is the lack of female-specific exoskeletons. The currently available exoskeletons are designed as a "one-size-adjusts-to-most" mentality [69], [70] without gender-specific models. One notable exception is the HeroWear exoskeleton [71] (Fig. 2(g)), which by design requires multiple sized top and bottom components. Many other companies do claim that their exoskeletons are designed to fit most people [33], [72]. However, some of these designs utilize chest plates (Fig. 2(e)-(f)), which women find uncomfortable [73], or they use waist belts designed for men that tend to slide upwards on women's hips [74]. As is evidenced by the increase in female-specific athletic equipment and outdoor clothing [75], [76] it is becoming clear that gender-specific equipment is necessary for performance and comfort. Several medical studies detail the anatomical and physiological differences between the male and female physique, especially when in reference to wearing devices on the body [77]–[79]. The same issue with female sizing also exists with PPE, where equipment designed for men provides less than ideal fit and protection for women [80]. This issue raises ethical concerns if an employer provides (or is only able to provide) exoskeletons that fit male workers well. Initial lab-based testing of exoskeletons for gender based fit has shown some positive results for female workers [48]. The research indicated there may be benefits for women who wear exoskeletons designed for men; however, there have been relatively few female subjects tested with exoskeletons, and much research remains to be done.

The lack of female-specific exoskeletons brings up new ethical issues related to Fairness surrounding the use of exoskeletons in industrial settings, where women make up nearly one-quarter of the production and manual material handling workforce [81]. It may be unethical to force female employees into wearing exoskeletons if they work less effectively, or doing so may lead to other problems due to a poorer fit (the Caring tenet). However, excluding female employees from certain jobs based on the lack of female-fit exoskeletons may be unethical as well (the Fairness tenet). Early research into customizable exoskeletons, not based on gender, has shown promising improvements in performance and comfort [82], [83]. Continuing this trend with gender-specific exoskeletons will likely yield increased user adoption, increased comfort, and will minimize these issues. In the meantime, maximizing both Caring and Fairness would imply purchasing several different brands of exoskeletons to increase the probability that one of them will fit women well. If none is found, employees could be offered other positions.

IV. OVERUSE AND OVERWORK

In an ideal scenario, exoskeletons would offset part of the effort to complete required tasks and the wearer would not be subjected to additional workloads, increased duties, or demands. Their unsupported joints would bear no difference in load with or without the exoskeleton. The wearer would use less energy to perform the same labor, and at the end of the day would be less fatigued. The result of wearing the exoskeleton would be additional protection for the user. Unfortunately,

market forces and productivity goals are likely to create different adoption pressures as companies seek to find a way to justify exoskeleton purchases or get a return on their investment. Workers may be overworked by management who believe their exoskeleton-wearing employees are also protected from injury.

Some of these issues are well-illustrated by the case where an exoskeleton can save its wearer energy. If exoskeletons decrease the metabolic energy required to perform repetitive lifting by up to 12% (e.g. as was shown in [84]–[86]), management may assume that workers should be able to utilize that saved energy to work harder or faster, accomplishing more in a given amount of time. However, this logic fails to consider how the work is distributed throughout the worker's body. While the joint(s) aided by the exoskeleton will use less energy and thus could potentially work faster, most exoskeletons leave other joints unprotected (e.g. a back exoskeleton does not aid the arms) and those joints will suffer from increased fatigue if the wearer works harder. Even in a scenario where an exoskeleton provides protection from the shoulders to the ground (e.g. the suitX MAX [31] or Sarcos Guardian XO [87] (Fig. 2(a))), the employee's body must still be in motion to accomplish the tasks, and could endure unanticipated stresses. Finally, working faster may lead to an increased risk of other types of injuries: working faster has been shown to increase the frequency of industrial and farm accidents [88]–[90].

The situation with overwork stemming from the use of an exoskeleton is distinct from the possibility of overwork with a newly-introduced power tool such as a jackhammer. With a jackhammer or other power tool, the user's productivity is automatically multiplied due to the machine doing the work. In contrast, with an exoskeleton, the user's body still is doing the vast majority of the work and the user is still susceptible to fatigue or accidents from hurriedness. Put another way, exoskeletons are not intended to increase productivity, with only a few exceptions such as some powered full-body exoskeletons enabling people to lift more than they could otherwise. However, many people might mistakenly believe that all exoskeletons ought to lead to increased productivity, potentially to provide an increased return on investment.

The ethical issue at the core of determining appropriate use cases is the possible trade-off between productivity and injury risk. If exoskeletons both reduce injury risk and improve productivity, there is no ethical quandary. However, if employers demand increased productivity it may come at the expense of increased injury risk. At the core, to maintain Caring for the employees, the employees should not be expected to do anything that would increase their injury risk or otherwise decrease their quality of work life (e.g. taking dramatically fewer breaks due to decreased fatigue). Controlled experiments with exoskeletons are likely the best way to determine the injury risk and other possible factors that affect employee welfare. The individuals making the decisions must be well-informed about the trade-offs and possible limitations of exoskeletons. It may ultimately prove that with the use of exoskeletons, productivity naturally increases even without employers demanding it do so: data suggests that improvements in safety naturally increase overall productivity [91]–[93].

Alternatively, with the possibility of a reduction in injuries leading to fewer missed days and less down-time, it is possible

that the primary return on investment comes from keeping workers healthy and maintaining production rather than increasing production. Decreasing injuries on the job could have the secondary effect of potentially decreasing workers' compensation claims as insurance companies begin to look into exoskeleton effects on preventing injuries [94]. Another solution is to pursue exoskeleton technology for the sake of improving the worker experience and well-being. If workers believe they are receiving a benefit from their use, perhaps that alone is enough justification. Any long term benefit, such as lower injury rates and decreased turnover may benefit the employer and should be considered a benefit, rather than a financial return. These benefits of exoskeleton use would actually be increasing the Caring of the company for its employees, in addition to any financial benefits they may provide.

V. ADDITIONAL CONCERNS

Beyond the physical implications of exoskeleton use are the social and psychological impacts an exoskeleton wearer may face. As many as 12% of the adult population suffers from Social Anxiety Disorder [95]–[98], a recognized mental health condition where individuals have adverse emotional and physical reactions to being in the spotlight or singled out. In situations where only a portion of the employees at a company wear exoskeletons, the individuals wearing exoskeletons may stand out and receive additional attention, wanted or not. Furthermore, some individuals may not like how they look while wearing an exoskeleton, especially if the exoskeleton fits them poorly or accentuates features they may not want noticed. These concerns are unique to exoskeletons as compared to PPE, since exoskeletons are frequently tight-fitting. In contrast, power tools are typically hand-held, so any extra attention from their use would not be nearly as significant.

These issues present an ethical concern with Caring and Respect if exoskeletons are introduced into a workplace and some existing employees are forced to wear them. Also, these concerns arise if exoskeletons are only introduced to a new employee after some a period of time, and the employee cannot evaluate how they will look while wearing the exoskeleton while deciding to accept the job or not. For some employees, this attention and the accompanying anxiety may be sufficient for them to quit their jobs. Companies who take this ethical question into consideration can work with employees to mitigate the impacts of attention by offering to transfer employees to other parts of the company that do not require exoskeleton use or finding other exoskeleton models that may look or fit differently.

Allowing employees to decide if they would like to wear an exoskeleton or not provides the employee with a level of autonomy. Similar to helmet laws for motorcyclists, there is a trade-off between the autonomy of the individual and the obligation to protect workers. In this instance, it is difficult to understand if an individual who chooses not to wear protection is able to accurately gauge and evaluate the potential injury and consequences [99]. Because of this, the argument for requiring the use of exoskeletons can be made for the health and well-being of the employees.

Additionally, exoskeletons may also present an opportunity for previously injured employees to return to work (RTW) sooner with their assistance [100]. Depending on the financial incentives, it could represent an ethical concern if management forces an employee to return from an injury prematurely. Specifically, this is an ethical concern with Caring if the exoskeleton would enable the employee to come back to work and do their job even while injured; if there was no exoskeleton, the worker would not be able to work at all. A similar but distinct situation would be if management forced an employee to return to work but the employee needed pain medication in order to be able to work. In this case, the pain medication just masks the pain, and the employee is still susceptible to further injury. With an exoskeleton, the exoskeleton may reduce work demands so the job is less strenuous. As such, while it is clearly unethical to force an employee to work through the use of pain medication, in the case of exoskeletons it is less clear.

In the case of exoskeletons, studies must be done to understand how exoskeletons may help or further hurt workers who are recovering from injuries, before allowing people to return to work earlier than they would under normal circumstances. To achieve Caring, it is ultimately important to prevent further worker injuries, but it is also beneficial to the employee if they can return as soon as they are able so they can make their normal wages; of course, this does not apply if they are getting paid as much as usual during their injury leave. Furthermore, one study found that for back injuries, an earlier RTW led to pain and function improving more rapidly [101], with the caveat that early RTW may not be beneficial if there are heavy physical burdens at the job. Exoskeletons may prove to be beneficial for RTW and employee health outcomes if they reduce physical demands on the employee.

VI. SUMMARY, POSSIBLE SOLUTIONS, AND OUTLOOK

Exoskeletons show great promise for assisting workers with physical labor and protecting them from injury; however, there is a need to address ethical questions regarding the compulsory use of exoskeletons in industrial settings. Mandating exoskeletons for workers is ethically concerning because of the imbalance of power between employers and employees and because there are currently no federal regulations governing their use. Some individuals will not be able to wear exoskeletons due to fit, size, or medical conditions; and some will not want to for other legitimate reasons. There is the possibility that an exoskeleton could cause secondary injuries, especially if employers demand increases in productivity to gain a return on their investment. In each of the situations identified in this paper, the ethical tenets of Trustworthiness, Respect, Fairness, and Caring from the Six Pillars of Character and Universal Moral Values for Corporate Codes of Ethics frameworks can be considered to guide policy decisions. In some cases, making exoskeleton use optional is a good idea, while in other situations where the risk of injury is much lower with an exoskeleton, it may be better to make them mandatory. In most circumstances, pilot programs where exoskeleton use is optional can be used to gather data about employee views, the exoskeletons' effect on injuries, and potential problems with fit and sizing. Offering several possible exoskeleton models, which employees can adjust themselves, is likely beneficial as

well. Overall, addressing ethical concerns prior to the widespread use of exoskeletons will facilitate their smooth adoption and potentially decrease employer-employee conflicts.

Exoskeleton adoption is forecast to accelerate over the next several years. Manufacturers are continuously refining and improving exoskeleton designs to make them more ergonomic and useful. Recent exoskeleton developments have included more specialized exoskeletons that are better suited for a specific application [102], models that have easier adjustability [55], and modular designs that can be customized to include different body parts [103]. Consumer exoskeletons will also become more commonplace as larger scale manufacturing and new designs bring exoskeleton costs in line with power tools. As the industry matures, more brands and sizing options for each type of exoskeleton will become available and employers may elect to allow employees to choose a specific model that is most comfortable while still meeting the support requirements. As the decrease in primary injuries (those protected by the exoskeletons) as compared to the increase in secondary injuries (those unintentionally caused by the exoskeletons) becomes more known, then injury-related ethical concerns will have more obvious solutions. Shoulder and back exoskeletons are the most common exoskeletons at the moment because they address the joints with the most common injuries and overall highest cost of injury for employers. But we expect that employers will look to exoskeletons to assist additional body parts as the benefits become more clear and exoskeletons (especially for niche applications) become cheaper. At some point exoskeletons may become a competitive advantage for employers, with employers advertising the fact that they have exoskeletons in order to recruit and retain workers.

While exoskeletons pose some novel issues as they are introduced to the workforce, there are also parallels from the prior introduction of new technologies that can be examined for lessons learned. While in other cases the effects on workers were only thoroughly studied after the technologies had been in use for some time, with exoskeletons there is the opportunity to address unforeseen issues at the outset. Actively studying and observing how exoskeletons are being used at both a broad and individual company level will provide researchers, decision makers, and regulators the ability to be proactive. This positioning will not only make the course of adopting exoskeletons more seamless but will result in better working conditions for employees.

Finally, because of their relatively recent appearance on the market, the long-term effects of exoskeleton use remain unknown. The longest published studies only span months [3], [104] and the longest that users have worn exoskeletons for work is a few years or less. Even in these short-term trials, some unforeseen issues have appeared such as discomfort and poor fit [3], [104]. As users wear exoskeletons for longer periods it is possible that larger, more weighty issues may arise. Abiding by ethical tenets would imply that mandatory exoskeleton use should be evaluated periodically after its implementation, to make sure that ethical tenets are being followed as well as possible.

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CONFLICT OF INTEREST STATEMENT

The authors hold a financial interest in Element Exo, Inc., which manufactures a back support exoskeleton.

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