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INVITED REVIEW

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An ethical assessment of powered exoskeletons: Implications from clinical use to industry and military contexts

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Abstract

Exoskeletons are technologies that can help to increase or improve mobility, dexterity, and strength. They can be used as assistive devices, to restore lost affordances, or for rehabilitation. While mechanical exoskeletons are passive and rely on the body's power for movement, powered exoskeletons are active mechanical systems that can assist or enhance a user's capacity, including in strength and performance. They also offer scope to augment or enhance beyond simple medical support, with potential in the future for superhuman power and strength. While these technologies present promising clinical opportunities, including for those who want to regain walking capacity, they also bring ethical questions, such as about data privacy and accessibility. In addition, the physical features of the technology can prove mentally, physically, and financially demanding, and may be deployed in contexts where user choice and autonomy is constrained. In this article, we discuss these issues, and raise some pertinent ethical questions, not all of which can be easily answered. We touch upon medical and therapeutic uses, for industrial and workplace settings, and in military contexts specially, given these are contexts where such technology may be required or even imposed. We argue that reasonable optimism for such technologies needs to be tempered by sufficient ethical assessment to identify and address barriers to research, development, and use. As well as managing any impacts and expectations for the health and wellbeing of users, the potential impact on autonomy and the risk of coercion, we have to consider what kind of data may be recorded or used, and the risk that these technologies could exacerbate existing inequalities or harms.

KEYWORDS

assistive devices, autonomy, enhancement technology, ethics, exoskeletons, rehabilitation, social issues, wearable robotics

1 | INTRODUCTION TO POWERED EXOSKELETONS

Exoskeleton technology is typically designed to be worn, with a view to increasing mobility, dexterity, strength, or some other bodily capacity. The structure of an exoskeleton encompasses joints that correspond with a human body[1] using *mechanical power* to amplify the user's own muscle strength.[2] As an enhancement technology, an exoskeleton can either increase typical capacity, be used as an assistive device, or restore affordances that have been lost. It can also be used as a rehabilitative device, for instance to improve bodily flexibility or strength, including in recovery from neurological conditions like stroke.[2] Mechanical exoskeletons like this rely on the body's own power and so are often described as *passive*. Passive exoskeletons can reduce the force needed for movement[3] and can therefore be used for work that is physically demanding. They can also be used to enhance performance or improve safety, especially for work that takes a user beyond comfortable scope of movement (overhead tasks), where they are putting their body into vulnerable positions (bending), or where there could be strain caused by repetition.[4]

Powered exoskeletons are *active* mechanical systems that can assist or enhance the user's capacity, whether in strength or performance. These are newer, heavier, and more complex technologies that may prompt visions of superhuman power or strength.[4] Because powered exoskeletons do not rely on the body's existing capacities, they can also be used where the body is either not able to undertake, say, a specific movement, or where a body cannot generate sufficient power for a movement or action. This includes for a person whose limbs are paralyzed or weakened,[3] such as people with paraplegia,[5] spinal cord injuries,[6] and cerebral palsy.[3] Some powered exoskeletons have this function through being controlled by “biosignals,” like the electrical activity within muscles or recorded from the brain, thereby bypassing possibly damaged muscles or limbs.[7] This has not only good clinical opportunities but also brings questions about, for example, data privacy, as neural recording can be involved.[8] There is, however, low clinical uptake of these technologies, with barriers and constraints related to training and time, knowledge and information, mental, physical, and financial resources, as well as user perception of clinicians and patients.[6] The way that exoskeleton technologies are powered also matters, for instance, whether they are closed-loop feedback systems with the body, or whether there are computational systems, especially where the latter offers scope for cyborg enhancement (cf. Ref. [9]).

The US Food and Drug Administration (FDA) classifies powered exoskeletons as class II medical devices[10] yet it is clear they offer scope to augment or enhance human capacity beyond simple medical support. For instance, some exoskeletons, powered or passive, are being developed for military purposes.[11] Regardless of purpose there are a number of technical matters to be addressed. For instance, whole-body powered exoskeletons are a significant challenge,[4] especially as they need to be adapted for individual users.[12] Yet experimentation phases might include only male subjects, who may even be “homogeneous in physique” (Ref. [4], p. 47909). In addition, technological solutions can engender trade-offs such as between strength and being nimble.[4] There could also be an increase in the risk of falling (or fear of falling) given the greater mass, and risks of new types of injury.[13,14] These risks can be exacerbated by user attributes related to body type or any co-morbidities.[6]

Meanwhile a technology may add scope for some tasks while impacting other faculties, such as cognitive capacity. For instance, an exoskeleton can increase a user's cognitive workload by shifting their focus to the unfamiliar weight or range of motion. Such issues may or may not be addressed with practice and training,[12] and further “can affect the user at various levels, from perceptions to actions” (Ref. [4], p. 47909). The success of the technology relies in part on not impeding or constraining the body's natural movement, but instead allowing for a full (or at least sufficient) range of movements, yet this can be difficult to achieve.[15] The fact that powered exoskeletons are worn means that they have close contact to the body and thereby apply pressure to the skin. For those who have sensitive or damaged skin, or who bruise easily, this can lead to discomfort, and with sustained or repeated use, chafing.[13] Other factors to consider include the ease of donning or removing the technology, and whether it leads to movements that are slow or rough.[14] In the next section, we explore some of these issues in relation to the medical and therapeutic use of exoskeletons, and then the use of powered exoskeletons in industry and military contexts. We expect these are contexts most likely in the short and medium term to drive powered exoskeleton development and use.

Before we do, it is worth noting that the funding of powered exoskeletons brings a number of broader ethical issues that we do not have space to address in this article beyond a brief comment. In short, while many exoskeleton technologies are developed as biomedical research and funded by research funding organizations and governmental agencies,[16] or through industry, some of the research is funded through military agencies (cf. Ref. [17]). These various organizations may have different or complementary aims, yet the technologies developed by each can easily find their way from one field or domain to another. A research program without military ambitions can nevertheless be adapted for military use later on, a possibility sometimes categorized as "dual use." Those who support and fund scientific research and innovation for medical and other ethically desirable purposes may however be unhappy to find the technologies later used in military or other non-therapeutic contexts.[8,18,19] The same is true for technologies created for medical purposes that are then adapted for more general enhancement purposes.[20] It may be that research funding organizations find it difficult to expect or even predict these outcomes, and once identified, such uses may be difficult to avoid, or for responsibilities to be assigned, including to developers and companies.[19] Yet, we consider it part of the responsibility of research funding agencies to assess the likelihood of such dual uses and to do so early on. This can be done through foresight analysis, by utilizing anticipatory ethics approaches, or by engaging with ethics by design approaches, for instance.[21] Regardless of the method, questions must be asked and answers provided, even if these remain tentative or uncertain.[15] We can expect that public and stakeholder perceptions and acceptance of these technologies, whether for rehabilitation or enhancement, will be affected by their dual use potential, which should therefore be given careful consideration. The inclusion of stakeholders in the design and development processes is therefore essential,[14] which ethics by design and similar approaches can help to enable.

2 | ETHICAL ISSUES

There are numerous ethical issues associated with powered exoskeleton technologies. For one thing, they are very costly. Current examples of exoskeletons which still require the use of crutches, are estimated at 80000 Euros each, which represents a clear accessibility barrier.[22] Meanwhile, studies often do not (cannot) address how the technologies will work for each individual who might use them. Yet without such knowledge we cannot be sure about the technical performance in practical terms, nor the impact on individual people.[12] Yet it is also clear that these kinds of technologies offer a lifeline to many people, for instance, paraplegic people who consider the possibility to walk again as essential to improve their quality of life (cf. Ref. [7]). In this section, we explore some of these issues in relation to three areas: health, industry, and the military.

2.1 | Powered exoskeletons in health

A 2014 survey asked stakeholders, including wheelchair users and healthcare professionals, for their perspectives on exoskeleton technology. The outcomes of the survey suggest health benefits, including long-term outcomes, are a top priority.[14] Other perceived benefits include for rehabilitation and the undertaking of everyday tasks, as well as for psychosocial benefits that come from eye-level social interaction, or the feelings of hope or confidence the technology can bring.[14] Yet, these technologies also raise a number of ethical issues. These ethical issues can be broadly considered under categories like safety and well-being (physical, psychological), access (equality, equity), and privacy and security (e.g. data protection),[23] among others.

Many of these issues have no simple solutions. For instance, the question of access. Practical issues like maintenance and repairs can restrict access to the technology and perpetuate division along lines of wealth or location. That said, making technologies more accessible can result in situations where people are *expected* to use them. This could lead some people to become dependent on the technology and thereby vulnerable to operational risks, or it being withdrawn from the market.[19] Access can also be affected by a change in personal circumstances, such as financial, or as related to health insurance categorization, and whether such technologies are considered rehabilitative or enhancement.[15] These issues are further affected by the hype or misinformation that surrounds these kinds of technologies, whether from overestimation of capabilities and benefits, or from the underreporting of risks and limitations.[19] As a result, users may be led to have unrealistic expectations of the technology and what it might offer them.[14]

The use of exoskeleton technology, whether powered or passive, leads to questions about human identity more generally, especially in relation to disabled bodies and what is considered healthy or "good." There is a real risk that these technologies can enable or perpetuate ableist views on what is a "normal" or ideal human body, and of disability as a problem to correct.[19] By helping someone to fit into existing social environments, and by enabling some typical capacities, that is, walking and standing, exoskeleton technologies have even been described as reinforcing normative ideals and thereby as "inherently conservative" (Ref. [15], p. 217). This is especially risky if people are then excluded because they cannot, or choose not to use these technologies. Disabled people who continue to use a wheelchair, for example, may face unfair discrimination because of ableist views about what counts as living well or getting better, or because wheelchair accessible infrastructure becomes deprioritized. Thus, costly technologies that improve only a few individual's lives or abilities may inadvertently shift focus from further improvements to accessibility that affects many more, whether in public spaces, or in the context of employment and accommodation.[19] Choosing to focus on improving bodies rather than environments needs to be recognized as a social and political choice, in addition to one that is medical or personal. Without careful consideration, exoskeletons could inadvertently run counter to narratives of disability as (at least partly) contingent on environment, typically referred to as the social model of disability.[24]

Finally, we need to consider that exoskeletons are (currently) very visible technologies. As with other visible assistive technologies like wheelchairs, we can expect them to be subject to a number of perceived biases or stigmas.[19] Given the perception of these technologies as somehow connected with superpowers, there are risks that people who use them will be seen as somehow beyond normal, or as merged with the technology. Some already see exoskeletons as a kind of cyborg technology,[15] while others note that they may cause existential struggles, including as related to body image and perceptions of bodily autonomy or who is in control.[19] When assessing the risks and benefits of passive and powered exoskeletons therefore, we have to take into account the complexity of the individuals who may use them (values, needs, preferences, experiences, etc.), while balancing these against societal views and the needs of those stakeholders who may never use them, whether from choice or circumstance, but who may nevertheless be impacted by them.

2.2 | Powered exoskeletons in industry

Just as with much already existing personal protective equipment (PPE) a role for exoskeletons in the workplace could be relevant for risky or labor intensive industrial settings. Passive exoskeletons could be used to correct for poor technique in lifting heavy or repetitive loads, and thus to reduce internal musculoskeletal injuries.[13] Such hardware is “passive” to the extent that it essentially braces the body in beneficial ways for the safe completion of given tasks. This kind of technology would have a role in injury prevention and as such have clear benefits both for employees and employers. The employee could benefit from fewer uncomfortable tasks, with less risk. From an employer perspective, less time lost due to injury in the workforce and less liability for rehabilitation following workplace injury could be big draws. Some employers may even mandate the use of exoskeletons for these reasons.[13]

Powered exoskeletons, meanwhile, would not simply brace the body and correct posture but take bodily activity as input or control for amplified strength and movement, or other kinds of output.[25] As such, these exoskeletons can operate in parallel with the body so as to steer or augment bodily action, or correct gait, and thereby produce a hybrid user-machine that can undertake greater or more difficult tasks in a work environment. Such exoskeleton functions would likely be of most interest to an employer who adopts this tool to aid task completion, boost capacity for task completion, or to contribute to co-produced human-machine task completion.

In the case that these technologies become more accessible and desirable to employers, how could an employee resist the introduction of powered exoskeletons to the workplace, given the expected benefits they might bring, and the investment they would represent by the employer? In many cases, their use would correspond with manual laborers whose median wage is low and perceived replaceability is high. As Pote et al. note[13] this power inequality creates a weak negotiating position for these workers, thereby compromising their ability to resist powered exoskeletons in the workplace.

Related to these workers' already perceived high replaceability, some powered exoskeletons could emerge with the capacity to learn from user movements and take them over, besides amplifying user input movements.

> The [input control] framework results in the novel capability of the exoskeleton to perform the task autonomously, without any human effort needed, once it has learned the objective from the user, while still being able to switch back to human control when required. We foresee the application of this control framework in occupational exoskeletons, allowing for increased assistance in accomplishing partially unknown, repetitive tasks, as make up a high proportion of industrial applications. (Ref. [25], p. 2)

In this case, the main aim is to relieve the user of repetitive work, and thereby represents a boon to the worker. Yet this could effectively train the exoskeleton as a wearable robot that may eventually take over the task, leading to worker obsolescence or workforce reduction.

Where workers are not averse to, or even welcome the use of powered exoskeletons in their work, we need to consider how representative this technology might be. As we noted above, exoskeletons are typically not developed with a broad range of users in mind. As with many technologies, powered exoskeletons are typically designed for an “average” male body size and type,[19] which impacts on fairness and accessibility.[13] This could lead to uncomfortable or unsafe powered exoskeletons available for use by female employees, or to the exclusion of women from using these exoskeletons. Were powered exoskeletons to become essential to the performance of some or many workplace tasks, this could effectively remove women and other marginalized people from certain labor forces.

Even where a powered exoskeleton fits a user well, it will still require user movement which, while supported by the exoskeleton, could result in changes to how forces are distributed throughout their muscles and body. This in turn can produce unfamiliar stresses and strains, or increase the risk of contact injuries, especially where the materials of the exoskeleton come into contact with skin or joints. Likewise, where the exoskeletons are powered they will generate heat, which coupled with the extra layers their use would entail wearing, could lead to thermal discomfort or overheating. This is especially important to consider where management might consider powered exoskeleton use to correspond with higher productivity, and begin to overwork employees. While the exoskeleton could be seen to relieve the intensity of work through aiding workers' lifting ability, if managers consider this a reason for them to work longer, new possibilities for overwork and harm or injury emerge. Workers may become especially vulnerable to exploitation where the use of exoskeletons bring non-negotiated changes to working conditions or performance expectations, and where their use leads to the perception of workers as somehow less than human.[19]

As Pote et al.[13] note, an exoskeleton encompasses the user's body which means they remain vulnerable to all the usual bodily experiences, like fatigue or injury, plus all the additional risks new and unfamiliar technologies can bring. As already alluded to, biosignals and neural recording are potential control mechanisms for exoskeletons. With these, questions arise regarding the appropriateness of having such data recorded in the workplace. It may seem innocuous to simply record neural signals relating to muscle contractions, but there could be some downstream ethical questions. Muscles contract with a force determined by neural inputs.[26] However, more neural signals than are required for muscular contraction are sent to the muscles. Research currently underway posits that this "motor null space" might be decoded such that insights on wider central nervous system activity could be forthcoming.[27] Were widespread use of neural-controlled powered exoskeletons to arise, a non-negligible repository of potentially sensitive data might result, akin to that derived from direct brain recording. While probably not "personal" data in a General Data Protection Regulation (EU GDPR) relevant sense, and not "medical" data, it seems nevertheless that such data ought to attract some attention.

Where worker safety can be improved, there is a prima facie case for implementing powered exoskeleton technology in a workplace as standard, and in a way that might be considered akin to just another piece of personal protective equipment (PPE). Where productivity can be enhanced, and this productivity is connected with greater prosperity or equitable distribution of resources, there can be a good case for powered exoskeletons in the workplace. As these possibilities are examined, and the chance for new forms of risk and of overwork emerge, it becomes clear that caution is advisable. Perhaps obviously, the emergence of novel technologies in the workplace ought to come with novel reflection on the position of workers. Powered exoskeletons involve a wide array of factors in a large sociotechnical system. By way of contrast, if the computer network is upgraded in an office we could expect the work of those employed in that office to benefit from faster Wi-Fi, more capacious cloud storage, etc. This might be a fairly unblemished "plus" for that office. Considering a workplace upgraded through the introduction of powered exoskeletons, however, we might have to consider ripple effects in terms of the nature of the work, its impacts on employees physically, as well as considering who has access to that work, and so on. As such, we foresee that they could, and likely would, bring wider changes than the introduction of other pieces of kit, including other types of PPE.

2.3 | Powered exoskeletons in the military

In an important sense, military personnel are a set of workers with highly specialized jobs. The labor they provide is closely aligned with national policies and security activities such that they may not be as free as some other workers to withdraw labor or dispute task distributions. On a very practical level, parallel with the situation that manual laborers face, military personnel do work that necessitates PPE. For instance, soldiers are routinely expected to carry very heavy loads. This can be in difficult environments such as high altitudes, which can cause issues with endurance capacity as well as musculoskeletal issues. According to one account, soldiers might carry 20 to 30 kilos of equipment as part of their normal, daily training, while they may be expected to carry loads of approximately 60 or 70 kilos when on deployment.[11] Exoskeletons offer solutions to these requirements, and are being adopted globally. A range of companies make exoskeleton systems that can enhance users' carrying capacity, as well as marching speed and range.[11] Powered exoskeletons, meanwhile, can further increase those capacities.

A risk emerges that, because of an emerging availability of powered exoskeletons especially, military decision makers, or national policymakers are incentivized to dampen discussion about whether what is newly technically possible is desirable or good. Augmenting military personnel through the development of powered exoskeletons might have prima facie benefits in terms of boosted load carrying and marching ability, for instance. However from there to an objectification of those personnel through technological means could open a door to unacceptable instrumentalization. At its limit, a kind of "super soldier" by means of quasi-roboticization emerges. Given development in this area is expensive — the military exoskeleton market is expected by some to grow to $3.5 billion by 2030[28]—it is not hard to imagine these pressures being real.

More broadly too, this could feed into a skewing of how military action was considered in general – the terrible nature of war, for example, could be further obscured by considerations of research and development, and value for money. Moreover, those tasked with carrying out military tasks, in being technologically enhanced, might come to be dehumanized through their quasi-roboticization. Again, this could prompt decision makers to change their values about how or when to pursue military options.

While autonomy is widely considered in medical ethical contexts, it may be less so in military contexts, where orders are expected to be followed. The individual soldier could be dehumanized and become a biological substrate in a military robot. The "multipurpose" nature of the powered exoskeleton could straightforwardly be taken to assume the flexibility of the soldier, in tension with the idea of specialist training or preparation. Moreover, with the growth in goal-flexibility permitted by these technologies, function creep and ethical jeopardy emerge whereby hitherto impossible military objectives may be sought. It would be important to consider that soldiers may have fewer legal avenues or rights in given circumstances, and their role in the research and development of potential powered exoskeleton applications ought to be carefully scrutinized.[8]

Battlefield, peacekeeping, or occupation norms might need to be adjusted to reflect exoskeleton-based inequalities so that unexpected outcomes from especially powered exoskeleton-enhanced deployments might be anticipated. In the same vein, novel exoskeleton-arms races might be anticipated that could have broad, possibly geopolitical, consequences. Were a historically small nation to invest heavily in military powered exoskeleton technology, that might transform the threat capacity in the eyes of their historical rivals or dominators. As such, the emergence of novel powered exoskeleton technology could prompt a rush to equip, or even prompt hostilities.

Lastly, given the expense of hardware, it ought to be anticipated that software integrity, updates, and security will be of high importance in military contexts, especially given the possibility for hacking, malware, or other cyberattacks. Imagine a scenario parallel with the workplace discussion above in which fewer soldiers are deployed for an objective, given their powered exoskeleton-enhanced capacity. Since an exoskeleton can walk *for* the user,[29] hacked software could permit enemy control over troop movement and activity. Less dramatically, through the data collected on user locations, activity, and so on, cyberespionage on an exoskeleton basis could produce hard-to-counter risks for pinpoint targeting of individual soldiers. The, admittedly still far-fetched, idea of the exoskeleton-enhanced "super soldier" could come with some serious new technical hazards.

3 | CONCLUSION

Technologies like powered exoskeletons need to be developed in ways that ensure they meet user needs, and identify and address barriers early in research and development. Developers should offer clear and realistic objectives, while engaging with user expectations, recognizing that these can change over time.[6] Ethical issues to consider include the health and wellbeing of users, autonomy and coercion, data recording and use, and the risk that these technologies could exacerbate existing inequalities or harms.

Powered exoskeletons can play a key role in the rehabilitation of people impacted by a range of conditions, including neurological, but the technologies are new and emerging, and potential benefits need to be balanced against other relevant factors including cost, resources, and accessibility.[3] More than this, the perspectives and preferences of individual users should be front and center of any decision making, where comfort is more than just a physical and practical issue to address[3] but also a psychosocial one. We need to balance the costs to buy and maintain a technology like this, and the payoff where such technology proves cost-effective, including to save money in the long term, such as through reduced future medical costs.[6] Considering the whole system is a vital first step in trying to account for how best to include or exclude exoskeleton technology in particular contexts.

Beyond rehabilitative applications for powered exoskeletons, there is also scope to consider where they can enhance existing bodily capacities.[20] Any discussion of enhancement brings problematic ideas of what counts as normal or ideal, what is better or improved. In the case of powered exoskeletons, *better* can relate to a broad range of actions, activities that include lifting, carrying, walking, marching, and so forth. This is a useful way to frame things where specific tasks are at stake, as in an industrial setting for example, where jobs could be aided through technology. But such ideas can obscure ethically concerning issues. For instance, to what extent can we take for granted what counts as bringing an impaired or disordered state to a healthy state, an inadequate one to an adequate one, insufficient to sufficient? Especially if those judgments concern not the needs of the individual but the needs of the context in which they live and work.

Value decisions must be made when it comes to deciding what is enough, what is desirable, and what remedies ought to be developed for what kinds of perceived deficits. In fact, such value judgments are inescapable and will be made throughout any such process, explicitly or implicitly. For instance, as already alluded to, the prevalence of typical male-scaled exoskeletons can be seen as having the effect in workplace and military settings of excluding typical female-scaled bodies.[18] Few would suggest that this kind of erasure was desirable or intended, yet it could be part of the consequences of a particular mode of exoskeleton technology development. To mitigate such eventualities, it seems minimally essential that implicit value judgments are made explicit through the careful development of exoskeleton technology in tandem with detailed ethical and value analysis.

The funding of powered exoskeleton research and development adds a further layer to this discussion, especially given expectations that public funded work will contribute to socially desirable goals. Yet to achieve these outcomes, we need to ensure that dual use scenarios are sufficiently explored, anticipated, and accounted for. Powered exoskeletons bring with them novel and possibly disruptive ethical issues, not least because the scope and advantages of technologies with enhancement potential remains speculative and difficult to predict.[20] Any risks need to be balanced against the value that powered exoskeletons can bring, especially for medical purposes. Relevant research and its funding ought therefore to be transparent, including as related to purposes and potential for dual use, and with a thorough risk/benefit analysis. Such analyses need to be realistic about the capacity and capability of existing and emerging technologies like powered exoskeletons, whereby their scope should be neither under- nor over-stated. Frameworks to measure ethical issues, and instruments for responsible research and compliance, can help here, including as related to enhancement, or to ensure suitable monitoring processes for the technologies once they are in production and use.[21]

AUTHOR CONTRIBUTIONS

The above listed authors confirm that both authors meet all four ICMJE criteria for authorship. Both authors jointly worked on the research, concept, analysis, writing, and revision of the article. There is no one else who fulfills the criteria that has been excluded as an author.

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CONFLICT OF INTEREST STATEMENT

There are no competing interests for either author.

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REFERENCES

1. Perry JC, Rosen J, Burns S. Upper-limb powered exoskeleton design. IEEE/ASME Trans Mechatron. 2007;12(4):408–17. https://doi.org/10.1109/TMECH.2007.901934
2. Lajeunesse V, Vincent C, Routhier F, Careau E, Michaud F. Exoskeletons' design and usefulness evidence according to a systematic review of lower limb exoskeletons used for functional mobility by people with spinal cord injury. Disabil Rehabil Assist Technol. 2016;11(7):535–47. https://doi.org/10.3109/17483107.2015.1080766
3. Bunge LR, Davidson AJ, Helmore BR, Mavrandonis AD, Page TD, Schuster-Bayly TR, et al. Effectiveness of powered exoskeleton use on gait in individuals with cerebral palsy: a systematic review. PLoS One. 2021;16(5):e0252193. https://doi.org/10.1371/journal.pone.0252193
4. Kim S, Srinivasan D, Nussbaum MA, Leonessa A. Human gait during level walking with an occupational whole-body powered exoskeleton: not yet a walk in the Park. IEEE Access. 2021;9:47901–11. https://doi.org/10.1109/ACCESS.2021.3068836
5. Wang D, Hu B, Chen W, Meng Q, Liu S, Ma S, et al. Design and preliminary validation of a lightweight powered exoskeleton during level walking for persons with paraplegia. IEEE Trans Neural Syst Rehabil Eng. 2021;29:2112–23. https://doi.org/10.1109/TNSRE.2021.3118725
6. Charette C, Déry J, Blanchette AK, Faure C, Routhier F, Bouyer LJ, et al. A systematic review of the determinants of implementation of a locomotor training program using a powered exoskeleton for individuals with a spinal cord injury. Clin Rehabil. 2023;37(8):1119–38. https://doi.org/10.1177/02692155231164092
7. Wang S, Wang L, Meijneke C, van Asseldonk E, Hoellinger T, Cheron G, et al. Design and control of the MINDWALKER exoskeleton. IEEE Trans Neural Syst Rehabil Eng. 2015;23(2):277–86. https://doi.org/10.1109/TNSRE.2014.2365697
8. Greenbaum D. Ethical, legal and social concerns relating to exoskeletons. ACM SIGCAS Comput Soc. 2016;45(3):234–9. https://doi.org/10.1145/2874239.2874272
9. Barfield W, Williams A. Cyborgs and enhancement technology. Philosophies. 2017;2(1):4. https://doi.org/10.3390/philosophies2010004
10. Miller L, Zimmermann A, Herbert W. Clinical effectiveness and safety of powered exoskeleton-assisted walking in patients with spinal cord injury: systematic review with meta-analysis. Med Devices. 2016;9:455–66. https://doi.org/10.2147/MDER.S103102
11. Jia-Yong Z, Ye L, Xin-Min M, Chong-Wei H, Xiao-Jing M, Qiang L, et al. A preliminary study of the military applications and future of individual exoskeletons. J Phys Conf Ser. 2020;1507(10):102044. https://doi.org/10.1088/1742-6596/1507/10/102044

12. Bequette B, Norton A, Jones E, Stirling L. Physical and cognitive load effects due to a powered lower-body exoskeleton. Hum Factors. 2020;62(3):411–23. https://doi.org/10.1177/0018720820907450
13. Pote TR, Asbeck NV, Asbeck AT. The ethics of mandatory exoskeleton use in commercial and industrial settings. IEEE Trans Technol Soc. 2023;4(4):302–13. https://doi.org/10.1109/TTS.2023.3264807
14. Wolff J, Parker C, Borisoff J, Mortenson WB, Mattie J. A survey of stakeholder perspectives on exoskeleton technology. J Neuroeng Rehabil. 2014;11(1):169. https://doi.org/10.1186/1743-0003-11-169
15. Sadowski J. Exoskeletons in a disabilities context: the need for social and ethical research. J Responsible Innov. 2014;1(2):214–9. https://doi.org/10.1080/23299460.2014.918727
16. Veneman JF, Lefeber D, Vitiello N. Review of exoskeletons for medical and service applications: ongoing research in Europe on wearable robots, with focus on lower extremity exoskeletons. In: Bai S, Virk GS, Sugar TG, editors. Wearable exoskeleton systems: design, control and applications. Institution of Engineering and Technology; 2018. p. 25–50. https://doi.org/10.1049/PBCE108E_ch2
17. Crowell HP, Park J-H, Haynes CA, Neugebauer JM, Boynton AC. Design, evaluation, and research challenges relevant to exoskeletons and exosuits: a 26-year perspective from the U.S. Army Research Laboratory. IISE Trans Occup Ergon Hum Factors. 2019;7(3–4):199–212. https://doi.org/10.1080/24725838.2018.1563571
18. Heathcote G. War's perpetuity: disabled bodies of war and the exoskeleton of equality. Aust Fem Law J. 2018;44(1):71–91. https://doi.org/10.1080/13200968.2018.1470447
19. Kapeller A, Felzmann H, Fosch-Villaronga E, Hughes A-M. A taxonomy of ethical, legal and social implications of wearable robots: an expert perspective. Sci Eng Ethics. 2020;26(6):3229–47. https://doi.org/10.1007/s11948-020-00268-4
20. Erden YJ, Brey PAE. Ethics guidelines for human enhancement R&D. Science. 2022;378(6622):835–8. https://doi.org/10.1126/science.add9079
21. Erden YJ, Brey P. SIENNA D5.3: methods for promoting ethics for human enhancement. Zenodo; 2021. https://doi.org/10.5281/zenodo.7266868
22. Universiteit Twente. Prof.dr.ir. Herman van der Kooij. Universiteit Twente; n.d. Available from: https://www.utwente.nl/en/research/researchers/featured-scientists/kooij/. Accessed 1 Nov 2023.
23. Jansen P, Brey P, Fox A, Maas J, Hillas B, Wagner N, et al. *SIENNA D4.4: Ethical analysis of AI and robotics technologies*. 2020. https://zenodo.org/records/4068083
24. Shakespeare T. The social model of disability. In: Davis LJ, editor. The disability studies reader. 4th ed. New York, NY: Routledge; 2013.
25. Beiter B, Srinivasan D, Leonessa A. Shared autonomy and positive power control for powered exoskeletons. Robot Auton Syst. 2024;171:104555. https://doi.org/10.1016/j.robot.2023.104555
26. Farina D, Negro F, Dideriksen JL. The effective neural drive to muscles is the common synaptic input to motor neurons. J Physiol. 2014;592(16):3427–41. https://doi.org/10.1113/jphysiol.2014.273581
27. Extracting the human motor null space from muscles—a new framework to measure human neural activity. CORDIS | European Commission; n.d. Available from: https://cordis.europa.eu/project/id/101077693. Accessed 2 Feb 2024.
28. Research and Markets Ltd. *Military exoskeleton—Global strategic business report*. n.d. Available from: https://www.researchandmarkets.com/reports/5140501/military-exoskeleton-global-strategic-business. Accessed 1 Nov 2023
29. Veneman JF, Kruidhof R, Hekman EEG, Ekkelenkamp R, Van Asseldonk EHF, van der Kooij H. Design and evaluation of the LOPES exoskeleton robot for interactive gait rehabilitation. IEEE Trans Neural Syst Rehabil Eng. 2007;15(3):379–86. https://doi.org/10.1109/TNSRE.2007.903919

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