

The Integration and Impact of Exoskeletons in Product Lifecycle Management (PLM)

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Abstract

This article explores the transformative role of exoskeletons in Product Lifecycle Management (PLM), examining their impact across various stages of product development, manufacturing, and maintenance. It delves into how these wearable devices enhance worker capabilities, improve safety, and contribute to overall efficiency and sustainability in industrial settings. The article discusses the application of exoskeletons in design and prototyping, their benefits in reducing physical strain and improving productivity in manufacturing, and their role in facilitating maintenance and repair tasks. Additionally, it examines the use of exoskeletons in training and simulation, highlighting their potential to create more realistic learning environments and improve skill acquisition. The article also addresses the contribution of exoskeletons to sustainability through extended workforce longevity and improved product quality. Finally, it explores the challenges of implementing exoskeleton technology, including cost considerations and adaptation requirements, before concluding with an outlook on future prospects and research directions in this rapidly evolving field. Throughout, the article emphasizes how exoskeletons are reshaping traditional approaches to PLM, offering insights into their potential to revolutionize industrial processes and workforce management.

Keywords: Exoskeletons, Product Lifecycle Management (PLM), Ergonomics, Industrial Sustainability, Workforce Augmentation

I. Introduction

The landscape of product development and manufacturing is continuously evolving, driven by the need for greater efficiency, improved worker safety, and enhanced product quality. In recent years, the integration of exoskeletons—wearable devices that augment human physical capabilities—has emerged as a promising solution to address the persistent challenges faced by workers throughout the product lifecycle. These challenges include physical strain, fatigue, and the risk of injury associated with repetitive tasks and heavy lifting.

Product Lifecycle Management (PLM), a comprehensive approach to managing a product from conception through design, manufacture, service, and disposal, stands to benefit significantly from the incorporation of exoskeleton technology. As industries strive to optimize their processes and maintain competitiveness in a global market, the potential of exoskeletons to revolutionize various stages of PLM has garnered increasing attention from both researchers and industry leaders.

Exoskeletons, originally developed for military and medical applications, have found new purpose in industrial settings. These devices range from passive systems that use springs or counterweights to reduce strain, to powered systems that actively assist in movement and force application. The versatility of exoskeletons allows for their application across diverse industries, including automotive manufacturing, aerospace, and construction, where they can significantly impact worker performance and well-being [1].

This article explores the multifaceted role of exoskeletons in PLM, examining their impact on design and development, manufacturing processes, maintenance and repair operations, and training simulations. Furthermore, it investigates the potential of these devices to contribute to sustainability efforts by extending workforce longevity and improving product quality. By analyzing the integration of exoskeletons into PLM, we aim to provide insights into the transformative potential of this technology for industrial efficiency, worker safety, and product innovation.

II. Exoskeletons in Design and Development

The integration of exoskeletons in the design and development phase of Product Lifecycle Management (PLM) has significantly transformed the way engineers and designers approach their work. This section explores the multifaceted impact of exoskeleton technology on prototype creation, ergonomic assessments, and the overall innovation process.

A. Assistance in prototype creation and testing

Exoskeletons have revolutionized the prototype creation and testing process by enhancing the physical capabilities of engineers and designers. These wearable devices allow for extended periods of work on prototypes, reducing fatigue and increasing precision. For instance, upper-body exoskeletons can support the arms and shoulders during intricate assembly tasks, enabling designers to maintain steady hands for longer durations. This increased endurance facilitates more thorough testing and refinement of prototypes, ultimately leading to higher quality end products.

Moreover, exoskeletons equipped with force feedback mechanisms provide designers with a unique opportunity to experience and evaluate the physical interactions with their prototypes more accurately. This hands-on approach allows for immediate identification of design flaws or areas for improvement, streamlining the iterative process of prototype refinement.

B. Enhancement of ergonomic assessments

One of the most significant contributions of exoskeletons in the design phase is their role in enhancing ergonomic assessments. By wearing exoskeletons, designers can simulate various user scenarios and physical interactions with products, gaining firsthand insights into the ergonomic implications of their designs. This experiential approach to ergonomic assessment goes beyond traditional computer simulations, providing a more nuanced understanding of how end-users might interact with the product.

Exoskeletons equipped with sensors can collect real-time data on body postures, movements, and forces exerted during product interaction. This quantitative data, combined with qualitative feedback from designers wearing the exoskeletons, enables a more comprehensive evaluation of product ergonomics. As a result, potential ergonomic issues can be identified and addressed earlier in the design process, leading to more user-friendly and safer products [2].

C. Impact on iteration and innovation processes

The integration of exoskeletons in design and development has significantly accelerated the iteration and innovation processes. By reducing physical limitations and fatigue, exoskeletons allow designers to engage in more rapid prototyping and testing cycles. This increased capacity for iteration fosters a more agile and responsive design process, where ideas can be quickly implemented, tested, and refined.

Furthermore, the use of exoskeletons encourages designers to explore more ambitious and physically demanding design concepts that might have been impractical or unsafe to prototype without such support. This expanded design space can lead to breakthrough innovations and novel product features that push the boundaries of what's possible.

The data collected from exoskeleton use during the design phase also contributes to a growing knowledge base that can inform future design decisions and industry best practices. By analyzing patterns in how designers interact with prototypes while wearing exoskeletons, companies can identify common challenges and opportunities for innovation across different product lines.

In conclusion, the incorporation of exoskeletons in the design and development phase of PLM has not only enhanced the physical capabilities of designers but has also fundamentally altered the approach to prototype creation, ergonomic assessment, and innovation. As exoskeleton technology continues to evolve, its role in shaping the future of product design and development is likely to become even more pronounced [3].

III. Application in Manufacturing

The integration of exoskeletons in manufacturing processes has ushered in a new era of worker support and efficiency. This section explores how these wearable devices are transforming the manufacturing landscape by addressing long-standing challenges related to physical strain, productivity, and workplace safety.

A. Reduction of physical strain and fatigue

Exoskeletons have proven particularly effective in mitigating the physical demands placed on workers in manufacturing environments. By providing targeted support to key muscle groups and joints, these devices significantly reduce the strain associated with repetitive tasks, heavy lifting, and prolonged standing. For instance, back-support exoskeletons can alleviate the stress on a worker's lumbar region during lifting operations, while upper limb exoskeletons can support the arms and shoulders during overhead work.

The reduction in physical strain translates directly to decreased fatigue among workers. This allows employees to maintain higher levels of performance throughout their shifts, leading to more consistent output and potentially longer, more sustainable careers in physically demanding roles.

B. Improvements in productivity and error reduction

The implementation of exoskeletons in manufacturing has led to notable improvements in productivity. By reducing fatigue and supporting proper body mechanics, these devices enable workers to maintain optimal performance for extended periods. This sustained efficiency often results in increased output and faster completion of tasks.

Moreover, the physical support provided by exoskeletons contributes to enhanced precision in manual tasks. With reduced physical strain, workers can focus more on the accuracy of their movements, leading to a decrease in errors and defects. This improvement in quality control is particularly valuable in industries where precision is paramount, such as electronics manufacturing or automotive assembly.

C. Safety enhancements and injury prevention

Perhaps the most significant impact of exoskeletons in manufacturing is in the realm of worker safety and injury prevention. By providing support and promoting proper body mechanics, exoskeletons help mitigate the risk of musculoskeletal disorders (MSDs) – a common concern in manufacturing environments. These devices assist in maintaining correct posture and reducing the forces exerted on the body during various tasks, thereby lowering the likelihood of both acute injuries and chronic conditions.

Exoskeletons also contribute to a safer work environment by reducing worker fatigue, which is a known risk factor for accidents and injuries. By keeping workers more alert and less physically stressed, exoskeletons indirectly contribute to overall workplace safety.

The implementation of exoskeletons in manufacturing settings has shown promising results in reducing workplace injuries and associated costs. A study conducted in a large automotive manufacturing plant found that the use of shoulder-support exoskeletons led to a significant reduction in shoulder fatigue and discomfort among assembly line workers, with potential long-term benefits for injury prevention and worker health [4].

PLM Stage	Exoskeleton Application	Benefits
Design and Development	Prototype creation and testing	Enhanced endurance for designers, improved ergonomic assessments
Manufacturing	Assembly line tasks	Reduced physical strain, improved productivity, decreased injury risk
Maintenance and Repair	Overhead work, accessing difficult areas	Improved task speed and quality, enhanced precision
Training and Simulation	Skill development	Realistic training environments, reduced physical strain during learning

Table 1: Applications of Exoskeletons in Product Lifecycle Management [2-6]

As exoskeleton technology continues to evolve, its application in manufacturing is likely to expand, offering even greater benefits in terms of worker well-being, productivity, and safety. The ongoing refinement of these devices, coupled with increasing adoption across various industries, points to a future where exoskeletons become an integral part of the manufacturing landscape, fundamentally changing how physical work is performed and managed.

IV. Exoskeletons in Maintenance and Repair

The application of exoskeletons in maintenance and repair operations has significantly transformed these critical aspects of Product Lifecycle Management (PLM). By addressing the physical challenges inherent in these tasks, exoskeletons are enhancing worker capabilities, improving efficiency, and contributing to higher quality outcomes.

A. Facilitation of access to challenging areas

One of the most notable benefits of exoskeletons in maintenance and repair is their ability to facilitate access to challenging or hard-to-reach areas. In industries such as aerospace, automotive, and large-scale manufacturing, workers often need to navigate confined spaces or work in awkward positions. Exoskeletons, particularly those designed for upper body support, enable workers to maintain difficult postures for extended periods with reduced fatigue. This enhanced endurance allows for more thorough inspections and repairs in areas that were previously difficult to access or required frequent breaks.

B. Improvement in task speed and quality

The physical support provided by exoskeletons translates directly into improvements in both the speed and quality of maintenance and repair tasks. By reducing physical strain and fatigue, workers can maintain focus and precision for longer periods. This sustained performance leads to faster completion of tasks without compromising on quality. For instance, in tasks requiring prolonged overhead work, such as aircraft maintenance, exoskeletons can significantly reduce arm fatigue, allowing technicians to work more efficiently and accurately.

C. Enhanced precision and reduced rework

Perhaps the most significant impact of exoskeletons in maintenance and repair is the enhancement of precision in task execution. The stability and support provided by these devices allow workers to perform delicate operations with greater accuracy. This increased precision is particularly valuable in industries where even minor errors can have significant consequences, such as in the maintenance of medical equipment or critical infrastructure.

The improved precision facilitated by exoskeletons leads to a reduction in rework – the need to redo tasks due to errors or substandard quality. This not only saves time and resources but also contributes to the overall reliability and safety of the maintained or repaired systems. By enabling workers to perform tasks correctly the first time, exoskeletons help streamline maintenance processes and improve the overall efficiency of PLM.

A study conducted in an industrial setting demonstrated the positive impact of exoskeletons on maintenance tasks. The research found that workers using upper body exoskeletons during overhead drilling tasks experienced significantly reduced shoulder muscle activity and reported lower levels of perceived exertion. This resulted in improved task endurance and accuracy, with potential long-term benefits for both worker health and task quality [5].

As exoskeleton technology continues to advance, its role in maintenance and repair is likely to expand further. Future developments may include more specialized designs tailored to specific maintenance tasks, integration with augmented reality for enhanced guidance, and improved ergonomics for even greater worker comfort and efficiency. These advancements promise to further revolutionize maintenance and repair operations, making them safer, more efficient, and more effective within the broader context of PLM.

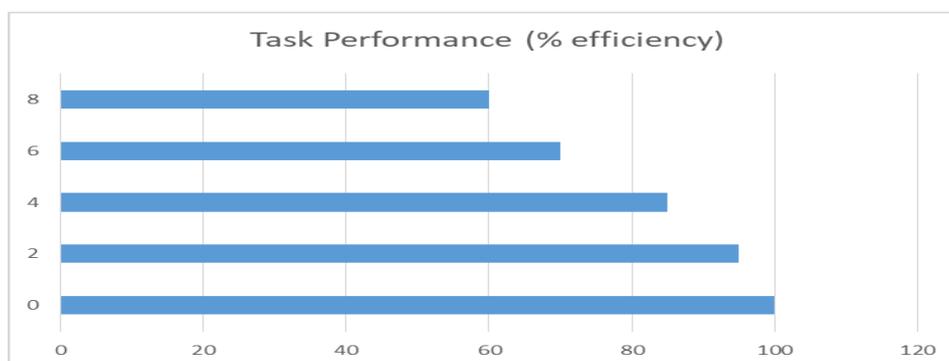


Fig 1: Impact of Exoskeletons on Worker Fatigue and Task Performance [4]

V. Role in Training and Simulation

The integration of exoskeletons into training and simulation processes has revolutionized the way organizations prepare their workforce for complex tasks in Product Lifecycle Management (PLM). This innovative approach enhances the learning experience, reduces physical strain during training, and allows trainees to focus more intently on mastering intricate skills.

A. Creation of realistic training environments

Exoskeletons play a crucial role in creating more realistic and immersive training environments. By simulating the physical demands of actual work scenarios, these devices allow trainees to experience the genuine feel of tasks they will encounter in their roles. For instance, in manufacturing or maintenance training, exoskeletons can replicate the weight and resistance trainees would face when handling real equipment or materials. This level of realism helps bridge the gap between theoretical knowledge and practical application, preparing workers more effectively for their on-the-job responsibilities.

B. Reduction of physical strain during skill development

One of the most significant advantages of incorporating exoskeletons in training is the reduction of physical strain on trainees. Learning new skills, especially those involving repetitive motions or heavy lifting, can be physically taxing. Exoskeletons alleviate this strain, allowing trainees to practice for longer periods without fatigue. This extended practice time is invaluable for skill development, as it enables more repetitions and a deeper internalization of the required movements and techniques.

C. Improved focus on complex task learning

By mitigating physical fatigue and discomfort, exoskeletons enable trainees to concentrate more fully on the cognitive aspects of their learning. This shift in focus is particularly beneficial when dealing with complex tasks that require high levels of concentration and precision. Trainees can dedicate more mental energy to understanding intricate processes, troubleshooting scenarios, or mastering advanced techniques, rather than being distracted by physical discomfort or limitations.

The use of exoskeletons in training and simulation also allows for a more gradual and controlled introduction to the physical demands of certain jobs. Trainers can adjust the level of support provided by the exoskeleton, gradually increasing the physical challenge as trainees become more proficient. This adaptive approach helps prevent injuries and builds confidence, leading to better-prepared and more capable workers.

A study conducted in an industrial training setting demonstrated the effectiveness of exoskeleton-assisted learning. The research found that trainees using upper-body exoskeletons during assembly task training showed improved learning rates and retention of complex procedures compared to those trained without exoskeletons. The exoskeleton group also reported lower levels of physical fatigue and higher satisfaction with the training process [6].

As exoskeleton technology continues to evolve, its role in training and simulation is likely to expand further. Future developments may include more sophisticated integration with virtual and augmented reality technologies, creating even more immersive and effective training environments. These advancements promise to further enhance the quality of workforce preparation, ultimately contributing to improved performance and safety across various stages of PLM.

VI. Contribution to Sustainability

The integration of exoskeletons in Product Lifecycle Management (PLM) processes has significant implications for sustainability, extending beyond immediate productivity gains to encompass long-term benefits for both the workforce and product quality. This section explores how exoskeletons contribute to a more sustainable approach in manufacturing and related industries.

A. Extension of workforce longevity

One of the most profound impacts of exoskeleton use in industrial settings is the potential extension of workforce longevity. By reducing physical strain and fatigue, exoskeletons help mitigate the risk of work-related musculoskeletal disorders (MSDs), which are a leading cause of early retirement in physically demanding professions. This support

allows workers to maintain their careers for longer periods, reducing turnover and preserving valuable expertise within organizations.

The reduced physical toll on workers not only extends their working lives but also potentially improves their quality of life post-retirement. By minimizing the cumulative wear and tear on the body, exoskeletons may contribute to better overall health outcomes for workers in the long term.

B. Improvement in product quality and lifespan

Exoskeletons contribute to sustainability through their positive impact on product quality. By enhancing worker precision and reducing fatigue-related errors, these devices help ensure more consistent and higher-quality outputs. Improved product quality often translates to longer product lifespans, reducing the frequency of replacements and, consequently, the overall environmental impact of production and disposal.

Moreover, the enhanced capabilities provided by exoskeletons allow for more intricate and precise manufacturing processes. This can lead to the development of more durable and efficient products, further extending their useful life and reducing the need for frequent replacements.

C. Reduction of waste and replacement frequency

The use of exoskeletons in manufacturing and maintenance processes contributes to waste reduction in several ways. Firstly, by improving product quality and durability, exoskeletons help create products that last longer, reducing the frequency of replacements and the associated waste. Secondly, the enhanced precision in manufacturing and maintenance tasks leads to fewer errors and less scrap material, directly reducing waste in the production process.

Furthermore, the improved efficiency and reduced fatigue associated with exoskeleton use can lead to more effective maintenance practices. This proactive approach to maintenance can extend the lifespan of industrial equipment and products, further reducing waste and the need for premature replacements.

A study conducted in an automotive manufacturing plant demonstrated the sustainability benefits of exoskeleton use. The research found that workers using lower-body exoskeletons during assembly tasks experienced significantly reduced physical strain and reported higher job satisfaction. This led to a decrease in absenteeism and turnover rates, contributing to workforce sustainability. Additionally, the study noted a reduction in error rates and improved product quality, suggesting potential long-term benefits for product lifespan and customer satisfaction [7].

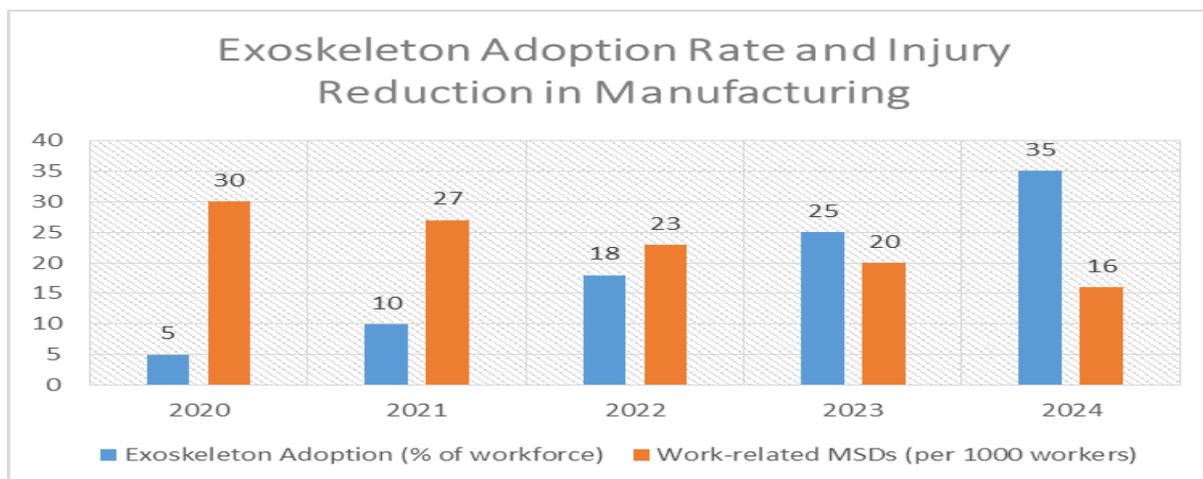


Fig 2: Exoskeleton Adoption Rate and Injury Reduction in Manufacturing [7]

As exoskeleton technology continues to evolve and become more integrated into PLM processes, its contribution to sustainability is likely to grow. Future developments may include more energy-efficient exoskeleton designs, integration with renewable energy sources, and improved recyclability of exoskeleton components. These advancements promise to further enhance the role of exoskeletons in creating more sustainable manufacturing practices and products, aligning with global efforts towards more environmentally responsible industrial processes.

VII. Integration Challenges and Considerations

While exoskeletons offer significant benefits in Product Lifecycle Management (PLM), their integration into existing processes is not without challenges. This section explores the key considerations and obstacles organizations face when implementing exoskeleton technology.

A. Implementation costs and ROI analysis

One of the primary challenges in adopting exoskeleton technology is the initial investment required. The costs associated with purchasing exoskeletons, modifying workspaces to accommodate them, and training staff can be substantial. Organizations must conduct thorough Return on Investment (ROI) analyses to justify these expenses.

The ROI calculation needs to consider various factors, including potential productivity gains, reduction in workplace injuries and associated costs, improvements in product quality, and the long-term benefits of extended workforce longevity. While the initial outlay may be significant, the long-term benefits often outweigh the costs. However, quantifying some of these benefits, particularly those related to worker well-being and long-term health outcomes, can be challenging.

B. Adaptation and training requirements

Integrating exoskeletons into the workplace requires a comprehensive adaptation and training program. Workers need to learn how to properly use and maintain the exoskeletons, which can involve a significant learning curve. This training process may temporarily reduce productivity as workers adjust to the new technology.

Moreover, the introduction of exoskeletons often necessitates changes in work processes and ergonomics. Existing workflows may need to be redesigned to fully leverage the capabilities of exoskeletons, requiring additional planning and potential disruption to established practices.

C. Potential limitations and areas for improvement

While exoskeletons offer numerous benefits, they also have limitations that need to be addressed. Current exoskeleton designs may not be suitable for all body types or tasks, potentially limiting their applicability. There are also concerns about the long-term effects of exoskeleton use on the human body, particularly regarding potential muscle atrophy or over-reliance on the technology.

Furthermore, the current generation of exoskeletons may have limitations in terms of battery life, range of motion, or adaptability to varied tasks. Addressing these limitations is crucial for wider adoption and effectiveness of the technology.

A study on the implementation of exoskeletons in an automotive manufacturing plant highlighted some of these challenges. The research found that while exoskeletons provided significant ergonomic benefits, there were initial challenges in worker acceptance and adaptation. The study emphasized the need for comprehensive training programs and gradual integration to overcome resistance and ensure effective use of the technology [8].

As the field of exoskeleton technology continues to evolve, many of these challenges are being addressed. Future developments are likely to focus on creating more versatile and adaptable exoskeletons, improving user comfort and acceptance, and reducing implementation costs. Additionally, as more long-term data becomes available on the effects of exoskeleton use, organizations will be better equipped to make informed decisions about their integration into PLM processes.

Overcoming these challenges will be crucial for the widespread adoption of exoskeletons in industrial settings. As the technology matures and best practices for implementation are established, the integration of exoskeletons into PLM is expected to become smoother, allowing more organizations to reap the benefits of this transformative technology.

Challenge Category	Specific Challenges	Potential Solutions
Cost and ROI	High initial investment, complex ROI calculation	Comprehensive cost-benefit analysis including long-term health benefits

Adaptation and Training	Learning curve, workflow redesign	Comprehensive training programs, gradual integration
Technical Limitations	Battery life, range of motion, adaptability	Ongoing research in materials science and AI integration
Long-term Effects	Potential muscle atrophy, over-reliance	Further studies on long-term physiological impacts

Table 2: Challenges and Considerations in Exoskeleton Implementation [8 ,9]

VIII. Future Prospects and Research Directions

The field of exoskeleton technology in Product Lifecycle Management (PLM) is rapidly evolving, with promising developments on the horizon. This section explores emerging technologies, potential new applications, and the long-term implications of exoskeletons for the workforce and product development.

A. Emerging technologies in exoskeleton development

Advancements in materials science, artificial intelligence, and sensor technology are driving the next generation of exoskeletons. Researchers are developing lighter, more flexible materials that can enhance the comfort and mobility of exoskeletons while maintaining their supportive properties. Smart materials that can adapt to different loads and movements are also being explored, potentially leading to more versatile and responsive exoskeletons.

Artificial intelligence and machine learning are being integrated into exoskeleton systems to create more intuitive and adaptive devices. These smart exoskeletons can learn from user movements and preferences, adjusting their support in real-time to optimize performance and comfort. Additionally, improvements in battery technology are addressing current limitations in operational time, paving the way for exoskeletons that can be used throughout entire work shifts without interruption.

B. Potential applications in new industries

While exoskeletons have found significant applications in manufacturing and maintenance, their potential extends to numerous other industries. In healthcare, exoskeletons could assist nurses and caregivers in patient handling, reducing the physical strain associated with these tasks. In agriculture, they could support workers during harvesting and other labor-intensive activities, potentially increasing productivity and reducing injuries.

The construction industry is another area where exoskeletons show promise, particularly in tasks involving heavy lifting or overhead work. In logistics and warehousing, exoskeletons could revolutionize material handling, allowing workers to move heavier loads with less strain. Even in office environments, exoskeletons designed for posture support could help prevent musculoskeletal disorders associated with prolonged sitting.

C. Long-term implications for workforce and product development

The widespread adoption of exoskeletons is likely to have profound long-term implications for both the workforce and product development. As exoskeletons become more advanced and integrated into various industries, they may reshape job roles and skill requirements. Workers may need to develop new competencies related to operating and maintaining these devices, potentially leading to the emergence of new specialized roles.

In product development, the enhanced capabilities provided by exoskeletons may allow for the creation of more complex and precise products. This could lead to innovations in design and manufacturing processes, pushing the boundaries of what's possible in various industries.

Furthermore, the long-term use of exoskeletons in the workplace may have significant implications for occupational health and workforce demographics. By reducing physical strain and extending the working life of employees, exoskeletons could contribute to a more age-diverse workforce, allowing older workers to remain active and productive for longer periods.

A recent study exploring the future of exoskeleton technology in industrial settings highlighted the potential for soft exosuits - lightweight, flexible exoskeletons that can be worn under clothing. The research suggests that these devices

could overcome many of the current limitations of rigid exoskeletons, offering greater comfort and adaptability across a wider range of tasks and body types [9].

As research in exoskeleton technology continues to advance, it is likely that we will see increasingly sophisticated and seamlessly integrated devices that enhance human capabilities across various industries. The ongoing development of exoskeletons promises to reshape not only how we work but also how we approach product design, workforce management, and occupational health in the coming decades.

Conclusion

In conclusion, the integration of exoskeletons into Product Lifecycle Management represents a significant leap forward in addressing longstanding challenges in manufacturing, maintenance, and product development. From enhancing worker safety and productivity to revolutionizing training methods and contributing to sustainability, exoskeletons are proving to be a transformative technology across various industries. While challenges remain in terms of implementation costs, adaptation, and technological limitations, ongoing research and development promise to overcome these hurdles. As exoskeleton technology continues to evolve, its potential applications are expanding beyond traditional industrial settings, hinting at a future where human capabilities are augmented across a wide range of professions. The long-term implications of this technology for workforce longevity, product innovation, and occupational health are profound, suggesting that exoskeletons will play an increasingly crucial role in shaping the future of work and product development. As industries continue to embrace and refine the use of exoskeletons, we can anticipate a more efficient, safer, and sustainable approach to Product Lifecycle Management, ultimately benefiting workers, businesses, and consumers alike.

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