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Smart Wearables in Ergonomic Applications: Recent Advances and Challenges in Human-Machine Integration.

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ABSTRACT

Smart wearables have become increasingly integral to ergonomic applications, particularly in healthcare, industrial work, and rehabilitation. These technologies offer significant benefits in enhancing human performance, reducing the risk of injury, and improving user comfort. Exoskeletons, one of the key smart wearable technologies, have seen widespread adoption in industrial settings, assisting workers in physically demanding tasks by alleviating muscle strain and promoting ergonomic posture. The application of machine learning within these wearables further enhances their adaptability, allowing for personalized support based on real-time feedback. In healthcare, wearable sensors provide critical insights into physiological and postural data, enabling continuous monitoring that supports long-term health and rehabilitation efforts. These wearables can track muscle activity, heart rate, and other vital signs, improving patient outcomes through ergonomic design that minimizes discomfort. In addition, soft robotic suits and passive exoskeletons have been developed to assist in mobility rehabilitation, offering a blend of comfort and functionality. Despite these advancements, challenges remain. Smart wearables must balance functionality with comfort, especially as many devices can be bulky or restrictive. The integration of artificial intelligence and machine learning offers solutions to some of these challenges, enabling wearables to adapt dynamically to user needs. However, technical issues such as data processing, sensor accuracy, and battery life continue to limit their widespread adoption. Future developments must focus on miniaturization, energy efficiency, and user adaptability to overcome these barriers, ensuring that smart wearables are both effective and practical for diverse ergonomic applications.

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Keywords: smart wearables, exoskeletons, ergonomic applications, human-machine integration, healthcare, rehabilitation, machine learning

1. INTRODUCTION

Smart wearables have become integral to ergonomic applications, particularly in fields where human-machine integration plays a vital role. Recent advances in wearable technology have led to the development of more effective systems designed to assist users in diverse sectors such as healthcare, industrial work, and rehabilitation. The integration of smart wearables into these sectors enhances human performance, reduces the risk of injury, and improves overall user experience.

One key area of focus is the use of exoskeletons in industrial settings. These wearable devices, particularly passive upper limb exoskeletons, have been explored extensively due to their ability to reduce muscle strain and improve user comfort. For instance, Lotti et al. (2022) discuss how machine learning algorithms embedded in soft robotic suits significantly enhance the interaction between the wearer and the device, leading to reduced muscle activity and lower metabolic rates during tasks. The incorporation of machine learning in the control architecture of these devices shows promise in making exoskeletons more responsive and adaptive to the user's needs, particularly in environments requiring repetitive physical labor. Such innovations highlight the importance of combining ergonomic design with advanced technology to optimize user support during physical tasks (Lotti, N. et al., 2022).

Another example of smart wearables in ergonomics is the development of wearable diffuse optical tomography (DOT) systems for healthcare applications. DeVore et al. (2023) present a high-performance, modular, wearable DOT system that provides enhanced flexibility and ergonomics while maintaining the accuracy of more traditional, stationary systems. This advancement illustrates how smart wearables can bridge the gap between functionality and user comfort, making them suitable for long-term use in both clinical and everyday settings. The modular nature of these systems, coupled with their wireless connectivity, offers substantial ergonomic benefits by reducing the burden on users during extended monitoring sessions (DeVore, H. et al., 2023).

In industrial settings, the use of exoskeletons has expanded beyond rehabilitation to encompass applications in heavy-duty tasks. The work by Madinei et al. (2022) on passive back-support exoskeletons illustrates their potential in reducing work-related musculoskeletal disorders (WMSDs). These devices, which operate without power supplies, are particularly suited for tasks that require manual material handling. By reducing the physical loads on workers' bodies, passive exoskeletons serve as a practical ergonomic intervention, promoting worker safety and reducing fatigue during prolonged tasks. The assistive torque profiles generated by these exoskeletons are tailored to the specific needs of the user, providing support where it is needed most, thus improving the overall ergonomics of the workplace (Madinei, S. et al., 2022).

In healthcare, smart wearables are proving to be beneficial in monitoring and managing conditions such as epilepsy. Villanueva et al. (2023) explore the use of minimally invasive wearable technology for epilepsy monitoring, focusing on the periauricular area. The system developed for this purpose integrates multiple physiological signals and offers an ergonomic design that minimizes interference with the user's daily activities. This application demonstrates how smart wearables can enhance user comfort while providing critical health monitoring in a non-invasive manner. By focusing on ergonomic design, such wearables ensure that medical devices can be used over extended periods without causing discomfort, thereby improving patient compliance and outcomes (Villanueva, G.M.B. et al., 2023).

Additionally, exoskeleton technology is being refined to meet the evolving needs of industrial applications. Izzat et al. (2024) provide a conceptual framework for optimizing the design of lower-limb exoskeletons for industrial use. This framework aims to align the design of exoskeletons with the objectives of Industrial Revolution 5.0, focusing on enhancing worker ergonomics and safety. By offering design recommendations tailored to the specific tasks performed in industrial environments, the framework helps manufacturers develop exoskeletons that not only support workers physically but also improve their overall well-being. This comprehensive approach to design optimization ensures that exoskeletons are both functional and comfortable, reducing the risk of injury and improving productivity in demanding industrial settings (Izzat, M.N. et al., 2024).

Exoskeletons designed for overhead work support, as examined by Paterna et al. (2024), further demonstrate the versatility of wearable technology in addressing ergonomic challenges. These exoskeletons are equipped with pneumatic artificial muscles, which provide mechanical support to workers performing repetitive tasks in industrial environments. The research highlights the importance of considering ergonomics in the design of transmission systems, which can either enhance the range of motion or improve user comfort depending on the design choices made. Such considerations are crucial for ensuring that wearable devices do not become a source of discomfort during extended use (Paterna, M. et al., 2024).
In the context of healthcare, wearable devices also play a crucial role in rehabilitation. Vaisali et al. (2023) provide a comprehensive review of upper limb exoskeletons, discussing their potential to assist individuals with physical disabilities. These devices, by enhancing rehabilitation

processes, offer a significant ergonomic advantage by reducing the physical strain on users and promoting recovery. The authors also highlight key factors such as biomechanics and control systems, which must be optimized to ensure that these devices are both effective and comfortable for long-term use. By addressing these factors, wearable exoskeletons can provide meaningful support in rehabilitation settings, improving patient outcomes (Vaisali, S. et al., 2023).

The integration of smart wearables in ergonomic applications also extends to fields like neurosurgery, where posture and ergonomics are critical. Zulbaran-Rojas et al. (2024) examine the use of wearable sensors to monitor the postural ergonomics of neurosurgeons during operations. This pilot study demonstrates how real-time biofeedback from wearable devices can help surgeons maintain better posture, reducing the risk of musculoskeletal disorders associated with prolonged static postures. By addressing ergonomic concerns through the use of smart wearables, the study offers insights into how wearable technology can enhance performance and well-being in high-stakes environments such as surgery (Zulbaran-Rojas, A. et al., 2024).

2. Wearable Technologies in Ergonomics

Wearable technologies have emerged as a pivotal tool in ergonomics, playing an essential role in monitoring physiological and biomechanical parameters. These devices, designed to improve both worker safety and performance, are increasingly being employed across various sectors, including healthcare, industrial settings, and rehabilitation. In ergonomic applications, wearables serve multiple functions, from assessing postural stress to evaluating muscle fatigue and physical strain during labor-intensive tasks.

One of the critical aspects of smart wearables in ergonomics is the ability to track physiological signals, such as heart rate, muscle activity, and body movement. For instance, wearable technologies used in minimally invasive surgery have demonstrated their effectiveness in monitoring surgeon stress levels and ergonomic conditions. Caballero et al. (2024) explore how electrodermal activity (EDA) sensors, combined with machine learning algorithms, can predict stress levels in surgeons during robotic-assisted procedures. By analyzing physiological parameters, wearable devices provide valuable data that can improve the ergonomic conditions of professionals working in high-stress environments. Such technologies offer the potential to enhance worker well-being by providing real-time feedback on physical stress and enabling adjustments to reduce fatigue and injury risk (Caballero, D. et al., 2024).

The evolution of wearable devices has brought about significant advancements in their design and functionality. These advancements have allowed for the creation of devices that are not only lightweight and comfortable but also highly effective in monitoring physical strain. Ahmad et al. (2024) conducted a systematic review on occupational exoskeletons, highlighting their potential to reduce work-related musculoskeletal disorders (WMSDs). By supporting the upper limbs and back during strenuous tasks, exoskeletons can alleviate the physical demands placed on workers, thus minimizing the incidence of injury. The integration of electromyography (EMG) sensors in these devices allows for the precise measurement of muscle activity, enabling researchers and practitioners to assess the effectiveness of exoskeletons in real-world industrial settings. The findings from Ahmad et al. (2024) indicate that exoskeletons consistently reduce muscle activity and fatigue, with an average reduction of 24% for the upper limbs and 20% for back support, underscoring their utility in physically demanding jobs (Ahmad, J. et al., 2024).

The application of wearable technologies extends beyond industrial use to healthcare and rehabilitation settings. In healthcare, wearable devices equipped with inertial sensors and surface electromyography (sEMG) sensors are frequently used to evaluate the ergonomic risks faced by professionals. A systematic review by Sabino et al. (2024) highlights the use of these devices in healthcare environments, where healthcare workers often engage in repetitive movements and awkward postures that increase the risk of developing WMSDs. The ability of wearables to provide continuous, non-invasive monitoring makes them particularly useful for assessing the long-term ergonomic risks faced by workers, allowing for timely interventions and ergonomic adjustments to prevent injury (Sabino, I. et al., 2024).

Wearables are also being developed for specific tasks, such as overhead work in industrial environments. Garosi et al. (2024) investigate the impact of a passive head and neck supporting exoskeleton designed to reduce muscle fatigue during repetitive overhead tasks. Their study found that the use of such an exoskeleton significantly increased the fatigue threshold of muscles in the neck and shoulders, effectively delaying the onset of muscle fatigue. This demonstrates the potential of wearables in reducing physical strain during demanding tasks, thereby improving worker endurance and reducing the likelihood of injury over time (Garosi, E. et al., 2024).

In construction, wearable technologies such as back-support exoskeletons have proven effective in mitigating the risk of WMSDs associated with material handling tasks. Liu et al. (2024) used vision-based algorithms to assess the ergonomic risk of construction workers performing material handling tasks with and without a wearable exoskeleton. Their findings revealed that the use of the exoskeleton reduced the ergonomic risk by 31.7%, primarily by improving posture and reducing the load on joints. This study highlights the importance of posture correction in preventing WMSDs, particularly in industries where workers are exposed to significant physical demands (Liu, Y. et al., 2024).

Wearable devices have also been successfully applied in more specialized ergonomic evaluations. Scataglini et al. (2023) conducted an observational study on dockworkers, using a wearable motion capture system to quantify the physical loads experienced during lashing tasks. Their findings revealed significant variations in the postural stress experienced by workers, with some exhibiting extreme wrist positions during certain tasks. Such insights underscore the value of wearables in identifying high-risk postures that may lead to injury, enabling employers to design individualized prevention programs aimed at reducing the occurrence of musculoskeletal disorders (Scataglini, S. et al., 2023).

The evolution of wearable devices has led to their increased adoption across various fields, with their ability to monitor both physiological and biomechanical parameters being particularly valuable. Kuratomi et al. (2023) provided a comprehensive review of wearable technologies, outlining their growing significance in healthcare, fitness, and workplace ergonomics. As wearable devices become more sophisticated, their potential to enhance human health and well-being continues to expand. These technologies not only allow for real-time monitoring but also provide feedback that can improve workplace productivity and reduce the incidence of workplace injuries. Kuratomi et al. (2023) emphasize the importance of considering job design when implementing wearable technologies, as the integration of such devices can impact worker autonomy and privacy (Kuratomi, D. et al., 2023).

3. Exoskeletons and Ergonomic Interventions

The development of exoskeletons has significantly advanced ergonomic interventions across various industries. Exoskeletons are wearable devices designed to support the body, enhance physical capabilities, and reduce the physical strain associated with tasks that involve repetitive motion or heavy lifting. These devices are being increasingly integrated into industrial and medical applications as a means of preventing work-related musculoskeletal disorders (WMSDs) and improving worker safety and performance.

Upper limb exoskeletons, in particular, have gained prominence in ergonomic studies due to their ability to reduce muscle strain and fatigue during tasks that require repetitive arm movements. Blanco et al. (2022) conducted an evaluation of an active upper-limb exoskeleton during overhead industrial tasks, demonstrating that the exoskeleton significantly reduced muscle activity and oxygen consumption. The exoskeleton's ability to reduce muscle strain by up to 64% in the biceps and 37% in the triceps highlights its effectiveness in minimizing the physical demands of repetitive tasks. Furthermore, the reduction in oxygen consumption and heart rate provides evidence of the exoskeleton's potential to enhance the overall physical well-being of workers (Blanco, A. et al., 2022).

Lower limb exoskeletons have also been developed for both industrial and medical applications. These devices are designed to provide support to the legs and lower back, reducing the strain associated with standing, walking, and lifting. The use of lower limb exoskeletons in construction and manufacturing has been explored by Gonsalves et al. (2022), who assessed the usability and comfort of a passive back-support exoskeleton during rebar work. The findings indicated that while the exoskeleton reduced discomfort in the lower back, users experienced increased discomfort in other areas, such as the shoulders and thighs. This highlights one of the key challenges in exoskeleton development: the need to balance support and comfort to ensure user acceptance and long-term use in industrial environments (Gonsalves, N.J. et al., 2022).

The medical applications of lower limb exoskeletons are equally significant, particularly in the rehabilitation of individuals with mobility impairments. Zhou (2023) conducted a survey on the use of actuated ankle-foot orthoses (AAFOs) in rehabilitation settings. These devices are designed to improve gait performance and reduce the metabolic cost of walking for individuals with lower limb impairments. The study found that AAFOs not only rectified pathological gaits in the short term but also led to long-term improvements in free walking performance. The study also emphasized the importance of human-robot interaction (HRI) in the design and control of these devices, as ergonomic considerations are essential to ensure user comfort and safety during extended use (Zhou, Y., 2023).

Passive exoskeletons, which do not rely on powered actuators, present unique challenges in terms of mechanical behavior and user experience. These devices are typically lighter and less complex than their powered counterparts, making them more suitable for tasks that require extended wear. However, the mechanical design of passive exoskeletons must account for the natural movements of the human body to avoid causing discomfort or restricting motion. Park et al. (2023) explored the design of the Elbow-sideWINDER, a passive elbow exoskeleton intended to assist with elbow flexion and extension during occupational tasks. The study demonstrated that the exoskeleton significantly reduced the activation of the biceps and triceps muscles during load-lifting tasks, but also highlighted the need for further refinement to minimize discomfort caused by joint misalignment. This underscores the importance of optimizing the mechanical behavior of passive exoskeletons to ensure their effectiveness in real-world applications (Park, D. et al., 2023).

In addition to the design challenges, the implementation of exoskeletons in ergonomic interventions also faces hurdles related to user acceptance and comfort. Ibrahim et al. (2023) examined the benefits and challenges of using wearable safety devices in the construction sector, finding that while exoskeletons can reduce the risk of injuries, their adoption is often hindered by factors such as cost, discomfort, and the perceived interference with work tasks. The study emphasized the need for further research to address these barriers and to develop exoskeletons that are both cost-effective and comfortable for long-term use in industrial settings (Ibrahim, K. et al., 2023).

Despite these challenges, the potential of exoskeletons to revolutionize ergonomic interventions is undeniable. The ability of these devices to reduce physical strain, prevent injuries, and improve worker performance makes them a valuable tool in industries where manual labor is prevalent. However, the success of exoskeletons in ergonomic applications will depend on continued advancements in design, user experience, and cost reduction.

The development of exoskeletons must also account for the diverse needs of users in different environments. For example, Hu et al. (2023) reviewed the use of wearable technologies and mixed reality in applied ergonomics, highlighting the importance of tailoring exoskeleton designs to specific tasks and user populations. The integration of real-time feedback systems, such as electromyography (EMG) sensors, can provide valuable insights into the physical demands placed on workers and allow for the optimization of exoskeletons to meet these demands. Additionally, the use of mixed reality systems can enhance the training and assessment of workers, improving the overall effectiveness of exoskeletons in reducing ergonomic risks (Hu, X. et al., 2023).

4. Wearable Sensors for Ergonomic Monitoring

Wearable sensors have become an essential tool in the evaluation of ergonomic risks in various workplace environments. These devices, particularly Inertial Measurement Units (IMUs), offer a way to track and analyze worker posture and movement, thus helping to assess and prevent work-related musculoskeletal disorders (WMSDs). The ability to monitor physiological parameters in real-time enables a more dynamic and personalized approach to ergonomic interventions. The widespread use of wearable sensors, including IMUs, optical systems, and wireless technologies, reflects the growing trend toward integrating advanced technologies in ergonomic applications.

IMUs are especially useful for tracking body posture and movement during tasks that involve physical strain. These sensors can measure acceleration, angular velocity, and orientation, providing detailed insights into joint movements and body mechanics. Baklouti et al. (2024) introduced a novel IMU-based system specifically designed to assess the risk of WMSDs. This system, applied in a cable manufacturing facility, allowed for detailed joint angle measurements and risk evaluations based on standardized methods like RULA and REBA. The system's ability to closely align with established risk assessment techniques, while providing a higher level of specificity, demonstrates the effectiveness of IMUs in ergonomic monitoring. The data collected by this system offered detailed insights into worker posture, enabling targeted interventions for issues such as tendonitis and lower back pain (Baklouti, S. et al., 2024).

The use of IMUs is not limited to industrial settings. Muller et al. (2022) explored the application of inertial motion capture to estimate back loading during manual material handling tasks. Their study demonstrated that IMUs can be used to estimate kinetic variables like the L5/S1 moments without the need for force measurements, providing a cost-effective solution for ergonomic risk evaluation in real-world environments. The correlation between IMU-derived data and optical motion capture systems suggests that IMUs can provide reliable data for assessing ergonomic risks, particularly in tasks involving heavy lifting (Muller, A. et al., 2022).

Beyond IMUs, wearable optical and wireless technologies are also increasingly employed in ergonomic assessments. Optical motion capture systems provide precise measurements of body movements and postures, allowing for detailed analyses of ergonomic risks. However, these systems are often complex and expensive, making them less accessible for widespread use in industry. In contrast, wireless wearable technologies offer a more flexible and cost-effective solution. These technologies can transmit real-time data on body movements, physiological parameters, and environmental factors, making them ideal for dynamic and continuous ergonomic monitoring.

DeVore et al. (2023) developed a high-performance wearable diffuse optical tomography system that combined wireless connectivity with flexible mechanics, offering a portable and ergonomic solution for monitoring physiological responses. The system's wireless capabilities allowed for real-time data collection without impeding the wearer's movements, making it highly suitable for ergonomic assessments in dynamic work environments. The use of optical systems in conjunction with wearable sensors provides a more comprehensive picture of the wearer's physiological state, thus improving the accuracy and relevance of ergonomic evaluations (DeVore, H. et al., 2023).

In healthcare and construction sectors, where the risk of musculoskeletal disorders is particularly high, wearable sensors have proven to be valuable tools. Abuwarda et al. (2022) reviewed the cross-benefits of wearable devices in healthcare and construction, highlighting their potential to improve workplace safety by monitoring worker fatigue and detecting hazardous postures. The study emphasized the importance of integrating wearable technologies into workplace health and safety programs to address ergonomic risks proactively. By continuously monitoring workers' physiological and biomechanical parameters, these devices enable the early detection of fatigue and strain, allowing for timely interventions that can prevent injuries and enhance productivity (Abuwarda, Z. et al., 2022).

The integration of wearable sensors into ergonomic assessments also extends to the development of more personalized intervention strategies. Wearable devices can capture individual-specific data, such as joint angles and muscle activation patterns, which can be used to tailor ergonomic solutions to the specific needs of each worker. For example, Sala et al. (2023) proposed a multi-parametric ergonomic assessment protocol that utilized IMUs and surface electromyography (EMG) to monitor head movement and muscle activation during laryngeal surgeries. The data collected through these wearable sensors provided detailed insights into the surgeon's physical strain, enabling the development of personalized interventions to reduce the risk of musculoskeletal discomfort. This approach demonstrates how wearable sensors can support the creation of ergonomic solutions that are both effective and individualized (Sala, E. et al., 2023).

5. Human Factors and User-Centered Design

Human-machine interaction in the context of wearable technology presents several challenges that must be addressed to ensure comfort, usability, and adaptability in ergonomic applications. The integration of smart wearables into daily and industrial tasks often encounters difficulties due to mismatches between human needs and machine functions. Ensuring that wearable devices fit seamlessly into a user's physical and psychological workflow requires a focus on user-centered design and the consideration of human factors.

One of the primary issues in human-machine interaction with wearables lies in the complexity of aligning the device's functions with the user's behavior and preferences. Mahmud et al. (2022) emphasized that the adoption of wearable exoskeletons in workplaces is hindered by various factors, including discomfort and lack of adaptability to the user's body movements. These issues are not just related to physical discomfort but also to the psychological adaptation required when using wearable devices. The difficulty in balancing device functionality with human ergonomics often results in poor user acceptance, particularly in environments such as construction where physical tasks are complex and varied. Mahmud et al. identified that while exoskeletons have potential in reducing musculoskeletal disorders (WMSDs), the mismatch between device mechanics and human ergonomics remains a significant barrier to their widespread adoption (Mahmud, D. et al., 2022).

User-centered design is essential to overcome these barriers, focusing on comfort, adaptability, and usability. The importance of designing wearable devices that users can wear comfortably over extended periods cannot be overstated. Lind et al. (2023) highlighted the role of wearable motion capture devices in preventing WMSDs by monitoring worker posture and providing real-time feedback. However, they also noted that these devices often face challenges related to wearability, as their bulkiness and lack of adaptability to individual users can limit their effectiveness. Devices need to be lightweight, flexible, and adaptable to different body shapes and movements to ensure user comfort and long-term usability (Lind, C.M. et al., 2023).

Moreover, the adaptability of wearable devices is crucial for ensuring that they can be used across a wide range of tasks and environments. DeVore et al. (2023) explored the use of modular wearable systems for ergonomic monitoring, noting that these devices must be flexible enough to accommodate different user needs and tasks. In their study, wearable systems that featured modular and wireless components were found to be more effective in real-world environments due to their adaptability and ease of use. This adaptability allows the devices to be used in dynamic environments, where users are required to perform a variety of tasks that involve different movements and postures. The ability to adjust the wearable device to suit the specific task at hand is a key factor in enhancing user experience and improving the overall effectiveness of wearable technology (DeVore, H. et al., 2023).

User experience with wearable devices is another critical factor in ensuring their successful integration into daily workflows. Kang and Mirka (2023) discussed the role of passive back-support exosuits in reducing muscle strain during posture-maintenance tasks. While these devices showed promise in reducing muscle activity, user feedback indicated that discomfort often occurred when the device was used for extended periods. This discomfort was attributed to poor fit and the restrictive nature of the device, highlighting the need for user-centered design improvements that prioritize comfort and long-term usability (Kang, S.H. & Mirka, G.A., 2023).

In terms of recommendations for improving wearables, a few key strategies have emerged from recent studies. One recommendation is the incorporation of user feedback during the design and development phases to ensure that the devices are tailored to user needs. Fani et al. (2022) proposed a multi-cue haptic system for ergonomic enhancement that utilized real-time feedback from the user to adjust the device's functions. By involving users in the design process, wearable devices can be better aligned with their expectations and requirements, ultimately leading to higher adoption rates and more effective ergonomic interventions (Fani, S. et al., 2022).

Another recommendation is the use of advanced materials and technology to improve the adaptability and comfort of wearable devices. Apicella et al. (2022) examined the role of EEG-based wearable systems in emotion recognition, noting that the number of electrodes and the placement of these sensors significantly affected user comfort and device accuracy. Reducing the number of channels and using flexible materials were suggested as methods to enhance the ergonomics of these devices, ensuring that they can be used in daily-life applications without causing discomfort or hindering performance. This focus on materials and design flexibility is crucial in developing wearable devices that can adapt to the user's body and environment (Apicella, A. et al., 2022).

6. Applications of Smart Wearables in Specific Domains

Smart wearables have emerged as transformative tools in ergonomic applications, significantly improving health monitoring, rehabilitation, and industrial practices. In healthcare, wearable devices have gained prominence for their role in monitoring postural alignment and physical stress. For instance, DeVore et al. (2023) presented a wearable system capable of diffuse optical tomography, offering high-performance monitoring in ergonomic applications. This technology allows continuous monitoring of physical parameters, facilitating real-time feedback on postural health and physical stress. Such wearables provide medical professionals and users with precise data on posture-related issues, helping to prevent long-term musculoskeletal complications. As a result, these systems serve as effective preventive tools for healthcare applications, particularly in clinical settings where continuous monitoring is essential for patients undergoing recovery from physical stress or injury (DeVore, H. et al., 2023).

In rehabilitation and assistance, wearable devices, including soft robotic suits, have shown considerable potential in assisting individuals with mobility challenges. These devices support rehabilitation by providing physical assistance, enabling users to perform movements that they would otherwise find difficult. Arciniega-Rocha et al. (2023) designed a smart wearable system for squat exercises aimed at injury prevention in amateur athletes. The system uses machine learning algorithms to detect incorrect postures during exercise, offering real-time feedback to prevent potential injuries. This technology can be adapted for rehabilitation, as it offers continuous feedback that helps users maintain correct postures during physical activities. By integrating soft robotics with advanced sensors and machine learning, these wearables assist users in maintaining proper movement patterns, promoting faster recovery and reducing the risk of further injuries (Arciniega-Rocha, R.P. et al., 2023).

In addition to soft robotic suits, passive exoskeletons have been developed to provide physical support in tasks involving repetitive or strenuous movements. Nieto et al. (2024) evaluated passive exoskeletons designed to assist workers involved in manual material handling. These devices reduce the physical load on users by providing mechanical support, particularly during lifting tasks. The study found that passive exoskeletons significantly reduced discomfort, especially in the lower back, shoulders, and knees, areas typically prone to injury during such tasks. By alleviating physical strain, these wearable devices enhance the user's ability to perform physically demanding tasks without suffering from the long-term effects of musculoskeletal disorders (Nieto, A. et al., 2024).

The industrial sector has also embraced wearable technologies, particularly exoskeletons, to mitigate the risk of musculoskeletal disorders. These disorders are prevalent in industries that require workers to engage in repetitive or physically demanding tasks, such as lifting heavy loads or maintaining awkward postures for extended periods. Beltran Martinez et al. (2022) explored the use of wearable inertial measurement units to track joint movements and assess fatigue-related risks in industrial settings. The study introduced a novel K-score system to quantify ergonomic risks based on joint angles, allowing real-time assessments of fatigue during manual tasks. This system provides immediate feedback to workers, helping them adjust their posture or movement to avoid fatigue-related injuries. The K-score system, combined with wearable technology, enhances the ergonomic safety of workers in industrial environments by providing precise, real-time data on physical stress and fatigue (Beltran Martinez, K. et al., 2022).

Wearable exoskeletons also play a pivotal role in reducing musculoskeletal stress in industries that involve physically demanding labor. Wu et al. (2023) investigated the application of cognitive ergonomics through wearable augmented reality (AR) devices in construction settings. The study developed an AR application that provided real-time instructions and feedback to workers, helping them complete tasks with improved posture and reduced physical strain. This approach highlights the potential of wearable technologies to enhance both physical and cognitive ergonomics, ensuring that workers maintain optimal postures while also improving task efficiency. By integrating AR with wearable devices, industries can reduce the incidence of work-related musculoskeletal disorders and improve overall productivity (Wu, S. et al., 2023).

Furthermore, industrial applications of smart wearables have extended to collaborative robotics, where human workers interact with robotic systems in a shared workspace. Lanzoni et al. (2022) proposed a system that combines full-body motion tracking with collaborative robotics to improve ergonomic assessments in manufacturing. The system monitors the worker's posture and provides real-time feedback on ergonomic risks, ensuring that the collaboration between human and robot minimizes physical strain. This integration of wearables with robotic systems represents a significant advancement in industrial ergonomics, where human-machine collaboration can optimize both productivity and worker safety. The use of wearable technology in these settings allows for continuous monitoring of physical stress, ensuring that ergonomic risks are identified and mitigated in real-time (Lanzoni, D. et al., 2022).

7. Challenges and Future Directions

Smart wearables have made substantial advancements in ergonomic applications, especially in the integration of human-machine interaction. However, several challenges remain in realizing their full potential for improving human performance and comfort. One of the critical challenges in developing ergonomic wearables is addressing the technical limitations related to the complexity of human biomechanics. Designing wearables that accommodate the dynamic nature of human movement requires detailed analysis of joint kinematics and muscle activation. In industrial settings, where tasks often involve repetitive movements or heavy lifting, wearable technologies such as exoskeletons must reduce physical fatigue and prevent musculoskeletal disorders (Basodan et al., 2021).

A common issue is the trade-off between the bulkiness of the device and its functionality. For instance, devices like exoskeletons can be cumbersome and restrictive, affecting the user's mobility and comfort. The design of soft robotics for wearables, such as the elbow assistive devices discussed by Mobedi et al. (2021), demonstrates efforts to balance device support and flexibility. The development of these assistive technologies focuses on minimizing constraints on the human body's natural movement. Similarly, exoskeletons for industrial applications, like the ones highlighted by Ippolito et al. (2020), aim to optimize ergonomics by integrating advanced robotic control with human motion. However, further miniaturization and improvements in energy efficiency are necessary to make these devices more practical for widespread use.

Another challenge is the integration of artificial intelligence (AI) and machine learning (ML) technologies into wearable devices. AI and ML have the potential to enhance the adaptability of wearables by learning user-specific movement patterns and predicting ergonomic risks in real-time. For example, AI-driven systems could continuously monitor a worker's posture and provide real-time feedback on ergonomic risks, as demonstrated by Armstrong et al. (2022). This adaptability is crucial for wearables used in diverse environments, where tasks and conditions vary significantly. AI and ML can also help in optimizing the control systems of wearables, allowing them to adapt dynamically to the user's needs, such as adjusting the level of assistance provided by an exoskeleton based on the task being performed (Zeng et al., 2020).

However, integrating AI and ML poses several technical challenges, particularly in terms of data collection and processing. Wearables must collect large amounts of biomechanical and environmental data, which raises concerns about sensor accuracy, data processing speed, and battery life. For instance, wearable systems that rely on inertial measurement units (IMUs) or electromyography (EMG) sensors for posture and muscle activity tracking need to ensure the data is processed in real-time to provide immediate feedback (Humadi et al., 2021). Additionally, these systems must be capable of filtering out noise and artifacts in the data to ensure accurate predictions. Improving sensor technology and developing more efficient algorithms will be essential in overcoming these challenges.

Looking forward, trends in the development of smart wearables for ergonomic applications emphasize miniaturization, energy efficiency, and enhanced user adaptability. Miniaturization will allow devices to become less intrusive and more comfortable for long-term use. For example, the wearable smart garments discussed by Cerqueira et al. (2020) have shown promise in providing ergonomic assessments while being lightweight and non-intrusive. As wearable components become smaller, more powerful, and energy-efficient, these devices will be able to perform more complex tasks without compromising user comfort. Advances in flexible and stretchable electronics, as explored by Basodan et al. (2021), will also play a pivotal role in making wearables more user-friendly by allowing them to conform to the body's contours more naturally. In terms of energy efficiency, current wearables often face limitations due to the need for frequent recharging, which can hinder their practicality in industrial settings or for long-term health monitoring. The use of low-power electronics and energy-harvesting technologies is being explored to address this issue. For instance, devices that can harness energy from body heat or movement to power sensors and communication systems will reduce the dependency on external power sources (Chander et al., 2020). In addition, developing low-power communication protocols, such as Bluetooth Low Energy (BLE), will extend battery life while maintaining the necessary data transfer rates for real-time feedback.

User adaptability is another critical area of focus for future wearables. As technologies evolve, wearables will need to be more intuitive and adaptable to individual user needs. Devices that can learn from the user’s behavior and adapt their operation accordingly will enhance the overall user experience and effectiveness. For example, wearables equipped with AI could provide customized feedback based on a user's specific ergonomic risks or rehabilitation needs, adjusting the intensity or frequency of feedback as necessary (Rusu et al., 2021). The ability to personalize devices to fit individual ergonomic profiles will improve both the efficacy and adoption of these technologies.

Despite these advancements, several barriers must be addressed before wearable technologies can be fully integrated into mainstream ergonomic applications. One significant challenge is user acceptance, which is often influenced by factors such as comfort, ease of use, and perceived effectiveness. For instance, in industrial settings, workers may be hesitant to adopt wearable exoskeletons due to concerns about movement restrictions or additional weight. Addressing these concerns through user-centered design, as emphasized by Laffranchi et al. (2021), is critical to ensuring the success of these technologies.

8. CONCLUSION

In conclusion, smart wearables have significantly advanced ergonomic applications across various industries, offering potential benefits in enhancing human performance, reducing the risk of musculoskeletal disorders (WMSDs), and improving overall worker safety and comfort. These technologies are increasingly being adopted in sectors such as healthcare, industrial work, and rehabilitation, where the need for ergonomic interventions is critical. Smart wearables, such as exoskeletons and wearable sensors, provide real-time feedback on physical stress, muscle fatigue, and postural health, allowing for timely ergonomic adjustments and interventions. The integration of advanced technologies such as machine learning and artificial intelligence has been a pivotal factor in the evolution of these devices. AI-driven systems enable wearables to learn user-specific patterns, providing dynamic and personalized assistance based on real-time data. This adaptability has the potential to make wearables more effective in diverse environments, where tasks and conditions can vary significantly. Wearable exoskeletons, for instance, are shown to reduce muscle activity and fatigue, thereby preventing injuries and enhancing productivity, especially in labor-intensive industries. However, the development of smart wearables also presents several challenges. The bulkiness and discomfort associated with some wearables, particularly exoskeletons, can hinder user adoption. Further miniaturization, coupled with improvements in energy efficiency, will be critical to making these devices more practical for everyday use. Additionally, the integration of AI and sensor technologies requires sophisticated data collection and processing capabilities, which can pose technical challenges related to sensor accuracy, data speed, and battery life. These challenges must be addressed to fully realize the potential of wearable devices in ergonomic applications. Looking ahead, future trends in smart wearables emphasize the need for miniaturization, flexibility, and energy efficiency. Developing more user-friendly, lightweight devices that are intuitive and adaptable to individual needs will be essential for promoting widespread adoption. Advances in flexible electronics, such as stretchable sensors and energy-harvesting technologies, are likely to play a crucial role in making wearables more comfortable and efficient. Moreover, the integration of wearable devices with real-time feedback systems and collaborative robotics will further enhance ergonomic interventions, ensuring that workers are better supported both physically and cognitively. Overall, while smart wearables have made significant strides in improving ergonomic practices, ongoing research and development are necessary to overcome the current limitations and fully integrate these technologies into mainstream applications. As the field continues to evolve, the focus should remain on designing devices that balance functionality, comfort, and user adaptability, ultimately leading to safer and more efficient workplaces.

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