Malaysian Journal of Ergonomics (MJEr)
Volume 6 Issue 1 2024 [90-104]

Human-Centered Ergonomics: Advancements, Challenges, and Future Directions in Industrial and Occupational Settings

Ahmad Humaizi Hilmi[1], Asna Rasyidah Abd Hamid[1] and Wan Abdul Rahman Assyahid[1]

[1] Fakulti Kejuruteraan & Teknologi Mekanikal, Universiti Malaysia Perlis

ABSTRACT

The field of human-centered ergonomics has evolved significantly, especially in industrial and occupational settings, where the focus is on optimizing worker performance and well-being through the integration of advanced technologies. This review paper explores the key advancements, challenges, and future directions in ergonomics as they relate to Industry 4.0, cognitive ergonomics, aging workforces, and sustainable manufacturing. With the rise of Industry 4.0, technologies such as motion capture, virtual reality, and autonomous systems have proven to be invaluable tools in addressing ergonomic risks while improving productivity. These innovations enable better task design and human-machine interactions, reducing both physical strain and cognitive load. However, the integration of technology also presents challenges, particularly for the aging workforce, which is more susceptible to ergonomic stressors. Ergonomic interventions such as assistive devices, like exoskeletons, and tailored workspace designs are critical for maintaining productivity and health among older workers. Furthermore, the review discusses the role of ergonomics in sustainable manufacturing, highlighting how ergonomic principles contribute to environmental goals by reducing energy consumption, waste, and physical strain. Cognitive ergonomics, which addresses mental workload and human-computer interaction, is another crucial area explored in this paper. As automation increases, optimizing human cognitive performance is essential to reducing errors and enhancing safety in complex work environments. In conclusion, while advancements in technology offer promising solutions to many ergonomic challenges, the future of human-centered ergonomics will require continued research and innovation to address the evolving needs of workers in diverse and technologically advanced environments. The ongoing development of ergonomic interventions that balance human well-being with industrial efficiency will remain central to the future of work.

Keywords: Human-centered ergonomics, Industry 4.0, cognitive ergonomics, aging workforce, sustainable manufacturing, motion capture, virtual reality

1. HUMAN-CENTERED ERGONOMICS IN INDUSTRY 4.0

In Industry 4.0, the integration of advanced technologies with human-centered ergonomics plays a crucial role in optimizing both worker well-being and productivity. Industry 4.0 refers to the ongoing transformation of traditional manufacturing and industrial practices using smart technology. Human-centered technologies, such as motion capture (MOCAP) and virtual reality (VR), have been increasingly utilized to address ergonomic concerns in modern assembly systems, focusing on improving the interaction between humans and machines to reduce ergonomic risks and enhance overall efficiency.

The application of motion capture technology allows for a more detailed analysis of workers' physical movements, identifying areas where awkward postures or excessive repetitive motions may cause strain or injury. This technology can be employed to redesign workspaces and tasks to minimize ergonomic risks. Virtual reality, on the other hand, is used to simulate work environments and train employees without the need for a physical workspace, providing a safe and controlled way to explore new ergonomic designs and test human-machine interactions before actual implementation. This has proven effective in industries such as automotive manufacturing, where optimizing the sequence of tasks and reducing cognitive load through better task design has led to fewer assembly errors and increased productivity (Real & Torres, 2024). By leveraging these technologies, organizations can strike a balance between human factors and operational efficiency, reducing ergonomic strain while maintaining or even enhancing productivity.

In the context of Industry 4.0, it is not only the integration of technology but also the optimization of assembly systems that is pivotal. Studies have shown that the sequencing of tasks can have a significant impact on both worker performance and error rates. In a field study within the car manufacturing industry, researchers assessed the impact of changing assembly operation sequences on the error rates for tasks such as installing child lock labels and sunroofs. By adjusting the task sequences, researchers found significant reductions in errors without negatively affecting productivity (Real & Torres, 2024). This demonstrates the potential for improving worker well-being and reducing errors by optimizing the flow of tasks to align with human cognitive and physical capabilities. This integration of human factors into the design of manufacturing processes reflects the broader goal of ergonomic optimization in Industry 4.0.

Ergonomic challenges are not limited to the reduction of errors and optimization of task sequences. The aging workforce presents another set of challenges for Industry 4.0. As workers age, they become more susceptible to ergonomic stressors such as musculoskeletal disorders, which can be exacerbated by the demanding physical requirements of modern manufacturing environments. A systematic review of the aging workforce in Industry 4.0 highlights the need for ergonomic interventions to address the specific needs of older workers, such as reducing physical strain and adapting work environments to their changing capabilities (Alves et al., 2024). This demographic shift necessitates the development of ergonomic solutions that are not only technology-driven but also human-centered, ensuring that older workers can continue to contribute productively without risking their health.

The integration of ergonomics into Industry 4.0 goes beyond physical factors, encompassing cognitive ergonomics as well. As technologies such as autonomous systems and artificial intelligence become more prevalent, the role of cognitive ergonomics in ensuring smooth human-machine collaboration becomes increasingly important. Research into adaptive autonomy, for example, explores how machines can adjust their level of autonomy based on the cognitive state and performance of human operators (Hauptman et al., 2024). This dynamic interaction allows machines to take over more tasks when human operators are under high cognitive load, reducing the risk of errors and accidents. Such an approach not only optimizes system performance but also helps to alleviate the mental strain on workers, contributing to their overall well-being.

In addition to optimizing assembly processes, Industry 4.0 technologies are also being applied to improve ergonomic outcomes in non-traditional industrial settings, such as forestry and waste management. For instance, chainsaw operators in the forestry industry face significant ergonomic challenges due to the physically demanding nature of their work, which involves prolonged awkward postures and repetitive motions. A study on the fatigue experienced by chainsaw operators found that the most strained parts of the body were the lumbar region, wrists, and hands, leading to a high risk of musculoskeletal disorders (Staněk et al., 2023). By applying ergonomic principles to task design and tool development, it is possible to reduce the physical strain experienced by these workers, thereby improving their long-term health and productivity. Similarly, in waste management, ergonomics plays a crucial role in optimizing worker well-being. A study on the ergonomic risks associated with door-to-door waste collection found that using larger bins with mechanized collection systems significantly reduced the ergonomic strain on workers (Degli Esposti et al., 2023). This case highlights the importance of considering ergonomic factors in the design of not only industrial processes but also logistics systems, ensuring that workers are not exposed to unnecessary physical risks.

The role of human-centered ergonomics in Industry 4.0 also extends to the design of autonomous systems, where the focus shifts from optimizing physical tasks to enhancing the user experience of human-machine interfaces. Research into the design of autonomous car interiors, for instance, emphasizes the importance of understanding user preferences and creating environments that prioritize comfort and ease of use (Kirkici et al., 2024). This human-centered approach ensures that the benefits of technological advancements are fully realized by creating systems that are intuitive and user-friendly, thereby reducing cognitive load and improving overall satisfaction.

2. ERGONOMIC RISKS AND CHALLENGES IN OCCUPATIONAL HEALTH

Ergonomic risks in occupational health span a wide array of factors, encompassing biological, chemical, and physical hazards. One of the most critical areas where these hazards manifest is in forestry and logging operations, where workers are exposed to significant ergonomic stressors. Chainsaw operators, in particular, face elevated risks of physical strain and fatigue, which can lead to musculoskeletal disorders and other long-term health issues. Studies have sought to explore the ergonomic challenges in this field, emphasizing the need for improved working conditions and equipment designs to mitigate these risks.

Chainsaw operators are frequently exposed to hazardous conditions, including prolonged awkward postures, forceful motions, and environmental stressors such as noise and vibration. Recent research has compared the effects of using petrol-powered and battery-powered chainsaws in real-world forestry operations to evaluate their impacts on worker health and productivity (Poje et al., 2024). The findings suggest that while both types of chainsaws have similar efficiency, battery-powered chainsaws offer some ergonomic advantages. These include lower noise exposure and reduced physical strain, as evidenced by lower heart rates during operation. The reduced noise levels are particularly noteworthy, as excessive noise is a known risk factor for hearing loss and other health issues in forestry workers.

Similarly, Neri et al. (2023) compared the noise and vibration levels produced by the latest models of lithium-ion battery-powered chainsaws with those of traditional petrol-powered models. The study found that battery-powered chainsaws can significantly reduce daily vibration exposure, by more than 50%, which directly contributes to lower risks of vibration-induced musculoskeletal disorders. However, the noise exposure of battery-powered chainsaws, while lower than petrol-powered models, still exceeded the upper exposure action value set by health and safety regulations. This highlights the importance of addressing not only the ergonomic aspects but also the environmental hazards associated with noise and vibration in logging operations.

In addition to noise and vibration, fatigue and physical strain are significant ergonomic concerns in forestry. Research on the fatigue experienced by chainsaw operators has shown that the lumbar region, wrists, and hands are the most affected body parts, with operators frequently reporting discomfort in these areas (Staněk et al., 2023). The physical demands of chainsaw operation, combined with awkward postures and repetitive motions, contribute to a high prevalence of musculoskeletal disorders in this workforce. The ergonomic design of chainsaws, including handle position, weight distribution, and vibration control, plays a crucial role in mitigating these risks. However, the physical environment, including uneven terrain and extreme weather conditions, further exacerbates the strain on workers.

Waste collection workers also face significant ergonomic challenges, particularly related to manual material handling. Ergonomic risks in this sector often stem from lifting, carrying, and handling heavy loads, which can lead to musculoskeletal injuries. A study on door-to-door waste collection found that the use of larger bins and mechanized systems can reduce the number of lifting and carrying operations, thereby minimizing the ergonomic risks (Degli Esposti et al., 2023). By reducing the frequency and intensity of manual handling tasks, such interventions can improve worker well-being and reduce the incidence of musculoskeletal disorders. Moreover, the study highlighted the economic benefits of improved ergonomic practices, demonstrating that optimizing the collection system not only enhances worker health but also reduces operational costs.

The ergonomic risks associated with fatigue and physical strain extend beyond the direct physical hazards of equipment use. For example, the cognitive workload and stress experienced by workers in physically demanding jobs also contribute to fatigue. Nadaffard et al. (2024) explored the cognitive workload of workers in Industry 5.0 environments, where the shift from purely physical tasks to more cognitively demanding tasks has introduced new challenges. Cognitive overload, combined with physical strain, can exacerbate the risk of fatigue and errors in occupational settings. The study advocates for the use of physiological measurements, such as heart rate and electroencephalography (EEG), to monitor workers' cognitive and physical states in real time. This approach enables the early detection of fatigue and provides opportunities for interventions that can reduce ergonomic risks.

Case studies on fatigue and physical strain further illustrate the complex interplay between ergonomic stressors and worker health in various industries. Montini et al. (2024) investigated the impact of collaborative robots (cobots) on human trust, anxiety, and workload in industrial settings. The integration of cobots in workplaces has been shown to alleviate some of the physical strain on workers by automating repetitive or physically demanding tasks. However, the success of cobots in reducing ergonomic risks depends on their design and collaboration modes. The study found that specific collaboration modes, such as those that allow workers to trigger cobot actions, resulted in lower mental workload and reduced physical strain. This suggests that ergonomic interventions in occupational settings must consider both the physical and cognitive demands placed on workers to optimize their well-being.

3. THE ROLE OF ERGONOMICS IN SUSTAINABLE MANUFACTURING

Ergonomics plays a pivotal role in shaping sustainable manufacturing practices, emphasizing the interrelationship between human well-being, environmental responsibility, and industrial efficiency. As industries strive toward achieving sustainability, ergonomics emerges as a critical tool in optimizing the work environment to enhance worker safety, health, and productivity while simultaneously minimizing environmental impact. The integration of ergonomic principles into sustainable manufacturing is increasingly recognized for its potential to create more efficient and environmentally friendly production systems.

The concept of sustainable manufacturing hinges on the balance between industrial growth and the reduction of environmental impact. Ergonomics contributes to this balance by designing work environments that reduce physical strain on workers, decrease energy consumption, and minimize waste production. Prunet et al. (2024) highlighted the growing importance of considering human factors in logistics and manufacturing systems, where integrating human characteristics into optimization models leads to more efficient, sustainable operations. The inclusion of ergonomic principles, such as reducing repetitive strain and promoting proper posture, can improve productivity while reducing the likelihood of injuries, thus fostering a more sustainable work environment.

The emerging concepts of eco-ergonomics and green ergonomics expand the role of traditional ergonomics by incorporating environmental considerations into the design of work systems.

These approaches emphasize reducing the ecological footprint of manufacturing processes while ensuring that workers are not exposed to harmful environmental conditions. Dovramadjiev et al. (2024) explored how visual ergonomics, particularly through the use of specialized software, can contribute to sustainability by promoting worker well-being. In this context, reducing eye strain and improving overall visual comfort not only enhances productivity but also reduces the need for frequent breaks, leading to more efficient use of time and resources.

In manufacturing environments, the ergonomic design of tools and workspaces can directly influence energy consumption and resource use. For instance, Pereira et al. (2023) demonstrated how augmented reality (AR) technologies can be employed in lean workplaces to optimize ergonomic conditions. By reducing the physical effort required in material handling and motion processes, AR can help minimize the need for excessive energy consumption in machinery, contributing to both improved worker safety and environmental sustainability. The integration of such technologies aligns with the goals of Industry 5.0, which seeks to balance human well-being with environmental considerations.

Another significant contribution of ergonomics to sustainable manufacturing is its role in waste reduction. By designing more ergonomic workstations and tools, manufacturers can reduce the occurrence of errors and defects, leading to fewer wasted materials and resources. This is especially important in industries where precision and accuracy are critical, such as electronics manufacturing. The optimization of human-centered work processes, as discussed by Ament et al. (2024), can result in more efficient production cycles with fewer material losses, thus contributing to the overall sustainability of the manufacturing process.

The concept of green ergonomics further extends the scope of sustainability by promoting the use of environmentally friendly materials and processes in ergonomic design. Matib et al. (2023) examined the implementation of technological ergonomic designs in oil and gas facilities, where the use of sustainable materials and energy-efficient systems is crucial for reducing environmental impact. The study underscores the importance of considering both worker health and environmental sustainability in the design of industrial systems. By adopting green ergonomics principles, industries can ensure that their operations are not only safe for workers but also environmentally responsible.

The integration of ergonomics into sustainable manufacturing practices is not without challenges. One of the primary obstacles is the need to balance ergonomic improvements with economic considerations. While ergonomic interventions can lead to long-term cost savings through improved worker productivity and reduced injury rates, the initial investment in ergonomic equipment and training can be a deterrent for some organizations. However, as Prunet et al. (2024) noted, the long-term benefits of integrating human factors into manufacturing systems far outweigh the short-term costs, particularly in terms of improved worker well-being and reduced environmental impact.

In addition to physical ergonomics, cognitive ergonomics also plays a role in sustainable manufacturing by enhancing workers' mental well-being and reducing cognitive load. Cognitive ergonomics focuses on designing tasks and systems that are mentally manageable for workers, thus preventing mental fatigue and errors. Trstenjak et al. (2024) discussed how cognitive ergonomics can be applied in Industry 5.0, where digitalization and automation require workers to interact with complex systems. By designing work processes that are cognitively ergonomic, industries can reduce the likelihood of mistakes that lead to wasted resources, thereby contributing to sustainable manufacturing practices.

Furthermore, the shift toward more human-centered approaches in manufacturing, as seen in Industry 5.0, emphasizes the importance of worker well-being in achieving sustainability goals. This shift is evident in the increasing use of technologies such as exoskeletons, which reduce the physical strain on workers while enhancing their productivity. Jakobsen et al. (2023) investigated the use of passive shoulder exoskeletons in logistics work, finding that such devices can significantly reduce muscle activity and perceived effort, contributing to both worker health and operational efficiency. By reducing the physical demands of manual labor, exoskeletons can also lower energy consumption in manufacturing processes, further supporting sustainability.

In conclusion, ergonomics plays a crucial role in advancing sustainable manufacturing by promoting worker health, reducing energy consumption, and minimizing waste. Concepts such as eco-ergonomics and green ergonomics highlight the potential for ergonomic interventions to contribute to environmental sustainability, while cognitive ergonomics ensures that workers can safely and efficiently interact with increasingly complex manufacturing systems. As industries continue to evolve, the integration of human-centered ergonomics into sustainable manufacturing practices will be essential in achieving a balance between economic growth and environmental responsibility.

4. HUMAN-CENTERED DESIGN IN AUTONOMOUS AND TECHNOLOGICAL SYSTEMS

Human-centered design has emerged as a fundamental approach in the development of autonomous and technological systems, focusing on optimizing human interactions within these environments. This perspective acknowledges that human factors must be central to the design process, especially in the context of systems that are increasingly driven by advanced technologies such as autonomous vehicles and adaptive autonomy systems. The challenge lies in balancing technological advancements with the need to ensure usability, safety, and efficiency for the human operator. This consideration is critical as the reliance on autonomous systems grows, with the goal of creating environments that prioritize both human and machine capabilities.

In autonomous vehicles, the human-centered approach involves the design of interfaces and controls that prioritize human operators' cognitive and physical capabilities. Gervasi et al. (2023) highlighted the importance of human-robot collaboration (HRC) in manufacturing, emphasizing how ergonomic considerations and human factors play a significant role in reducing physical strain and improving cognitive interaction. The same principles apply in autonomous vehicle design, where operators must be able to effectively monitor, control, and override the system when necessary. This ensures that human operators remain engaged and in control, even as vehicles become more self-sufficient.

The development of autonomous systems also necessitates the adaptation of human factors to emerging technologies, particularly in the realm of adaptive autonomy. Zarei et al. (2023) explored the integration of artificial intelligence (AI) into human factors analysis, noting that traditional methods of evaluating human interactions are often insufficient in complex systems driven by AI. In autonomous systems, adaptive autonomy refers to the system's ability to adjust its behavior based on the operator's needs, preferences, and environmental conditions. This requires a deep understanding of human behavior, cognitive load, and situational awareness to ensure that the system responds appropriately without overwhelming the operator.

One of the key challenges in human-centered design for autonomous systems is ensuring that the system is intuitive and easy to use, even in high-stress or dynamic environments. Zigart et al. (2023) conducted a study on multi-assistance systems in manufacturing, finding that skilled workers often experience better compatibility with cognitive and physical assistance systems when these systems are designed to align with their expertise and values. In autonomous vehicles, similar principles can be applied by designing interfaces that provide clear and concise information to the operator, allowing them to make quick and informed decisions without experiencing cognitive overload.

The rise of autonomous systems has also led to the need for more sophisticated models of human-machine interaction. He et al. (2024) discussed the evolution from digital human modeling (DHM) to human digital twins (HDT), which offer a more dynamic and real-time approach to understanding human interactions with technology. HDTs integrate AI and real-time data to provide continuous monitoring and assessment of human behavior, allowing for more personalized and adaptive systems. This approach is particularly relevant in autonomous systems, where the ability to predict and respond to human actions in real-time is essential for ensuring safety and efficiency.

Furthermore, the design of autonomous systems must account for the potential for human error, especially in critical environments such as healthcare or industrial settings. Mahendran et al. (2024) conducted a review on the role of non-technical skills (NTS) in robotic-assisted surgery, emphasizing the importance of communication, teamwork, and situational awareness in ensuring patient safety. These same non-technical skills are crucial in the design of autonomous systems, where the operator must be able to effectively interact with the system while maintaining situational awareness and managing potential errors.

In addition to cognitive and physical considerations, human-centered design in autonomous systems must also address the emotional and psychological aspects of human interaction. Reese et al. (2024) highlighted the importance of designing ergonomic systems for users with specific needs, such as individuals with arthritis. In autonomous systems, ensuring that the design is inclusive and accessible to a diverse range of users is essential for promoting widespread adoption and usability. This includes designing interfaces that are adaptable to different skill levels and physical abilities, ensuring that all users can effectively interact with the system.

The integration of human factors into the design of autonomous systems is not without its challenges. One of the primary obstacles is ensuring that the system is flexible enough to accommodate the wide range of human behaviors and preferences. Fadden (2024) noted the complexity of trauma resuscitation, where multiple specialists must work together in a dynamic and high-stress environment. Similarly, in autonomous systems, the design must account for the unpredictability of human behavior, ensuring that the system can adapt to different scenarios while maintaining safety and efficiency.

5. ERGONOMICS IN AGEING WORKFORCES

In modern industrial and occupational settings, ergonomics plays a vital role in addressing the challenges faced by an ageing workforce. With populations in many parts of the world ageing, more workers are staying in the workforce longer, resulting in a pressing need for ergonomic interventions to sustain productivity and well-being. The demands of modern production systems, which are often highly automated and technologically advanced, can place considerable strain on ageing workers. This is particularly evident in roles requiring repetitive physical tasks, long hours, and manual labor. The ageing process naturally leads to a decline in physical capabilities, which can exacerbate ergonomic challenges, such as musculoskeletal disorders (MSDs), fatigue, and cognitive decline.

Gabrielson and Wei (2024) studied musculoskeletal pain in surgical settings and highlighted that work-related physical strain remains prevalent despite advancements in ergonomics. Their findings, which focused on surgeons, have broad applicability to industrial settings where similar ergonomic principles apply. The study found that musculoskeletal pain was common, particularly in the neck, shoulders, and lower back—areas often strained in physical labor. This reflects the broader challenge faced by ageing workers in industries that demand prolonged periods of physical exertion. The prevalence of such issues underscores the importance of ergonomic interventions, such as redesigning workstations and tools to better accommodate the physical limitations of older workers, to mitigate these risks.

In forestry work, where workers handle heavy and dangerous equipment like chainsaws, Landekić et al. (2023) found that ergonomic risks associated with incorrect postures and movement patterns could be mitigated by implementing better postural habits and interdisciplinary cooperation. This approach could be beneficial in industrial settings, where similar interventions could prolong the working lives of older employees by reducing the incidence of injury. For instance, ensuring that workers are trained in ergonomic postures and movements, along with the use of assistive technologies such as exoskeletons, could significantly reduce the physical strain associated with manual labor.

The role of assistive technologies, including exoskeletons, is increasingly being recognized in ergonomic interventions for ageing workforces. Mohamad et al. (2023) explored the potential of passive exoskeletons to support tasks such as harvesting in physically demanding environments. Their research showed that exoskeletons could alleviate physical strain, particularly in tasks requiring repetitive motion and awkward postures. By reducing physical exertion, these devices can enable older workers to continue performing physically demanding tasks, potentially extending their working lives. The benefits of such technologies are particularly relevant in sectors where manual labor is essential and unavoidable.

In addition to the physical challenges, cognitive factors also play a role in the ergonomic challenges faced by ageing workers. As workers age, cognitive decline can affect their ability to adapt to new technologies and processes. Yasue et al. (2025) emphasized the importance of resilience and the ability to manage multiple disturbances in production systems. Ageing workers may find it more difficult to cope with the increasing complexity and variability in modern production environments. Ergonomic interventions that simplify tasks, reduce cognitive load, and provide intuitive interfaces could help older workers maintain high levels of performance despite these challenges.

Moreover, ageing workers often face difficulties in adapting to the increasing automation and digitalization of industrial processes. The introduction of collaborative robots (cobots) in production lines, as studied by Lagomarsino et al. (2023), highlights both opportunities and challenges for older workers. While cobots can reduce physical strain by taking over repetitive tasks, they can also increase cognitive demands by requiring workers to monitor and interact with the machines. To address this, cognitive ergonomics must be considered alongside physical ergonomics. Training programs that help workers adapt to these new technologies and ergonomic designs that reduce the cognitive load are essential in ensuring that older workers can continue to contribute effectively in such environments.

An additional aspect of ageing workforces is the potential for prolonged working life, which often comes with health-related challenges. The relationship between prolonged physical activity and musculoskeletal strain was examined by Staněk and Mergl (2024), who found that factors such as body mass index (BMI) and length of service significantly influence the physical stress experienced by workers. These findings suggest that ergonomic interventions must be tailored to the specific needs of older workers, taking into account their physical condition and work history. Interventions such as providing adjustable workstations, incorporating more frequent breaks, and promoting the use of ergonomically designed tools could alleviate the cumulative physical stress that builds up over a long career.

In addition to physical ergonomic interventions, workplace design plays a crucial role in supporting ageing workers. Attia et al. (2023) demonstrated how implementing ergonomic principles in the design of production lines could improve performance and reduce strain. For older workers, adjusting the layout of workspaces to minimize unnecessary movements, reducing the physical demands of tasks, and creating more accessible work environments could significantly improve their ability to continue working safely and efficiently.

6. DISASTER ERGONOMICS: ADDRESSING ESCALATING CHALLENGES

Disaster ergonomics has emerged as a critical discipline addressing the growing complexities of managing disasters, particularly in industrial and occupational settings. The increasing frequency and severity of natural and human-made disasters necessitate a comprehensive approach to disaster management, with ergonomics playing a pivotal role in enhancing response efficiency, safety, and human performance during these events. Ergonomics, traditionally concerned with optimizing human interaction with systems and environments, is now being applied to disaster management systems to ensure that human capabilities are effectively leveraged while minimizing risks to responders and affected populations.

In disaster management, human factors are of utmost importance, as decisions made under extreme stress, time constraints, and hazardous conditions can significantly impact outcomes. The integration of ergonomics into disaster management systems focuses on optimizing human-machine interaction, task design, and environmental conditions to reduce errors, enhance situational awareness, and improve overall system performance. This approach not only benefits first responders but also aids in the design of disaster response protocols that are more intuitive and aligned with human cognitive and physical limitations.

One critical aspect of disaster ergonomics is the design and implementation of user-friendly equipment and tools that can be efficiently operated under stressful and time-sensitive conditions. For example, wearable devices, such as exoskeletons, have been developed to assist responders in handling heavy equipment or performing physically demanding tasks without risking injury. Botti et al. (2023) discuss the potential of exoskeletons in supporting manual material handling tasks, highlighting how such devices can reduce the physical strain on workers, which is particularly relevant during disaster recovery operations where prolonged and intense physical labor is required. Their study emphasizes the need for further research into the long-term effects of using these devices in high-pressure environments like disaster zones, where both physical and cognitive demands are elevated.

Another critical element in disaster ergonomics is communication and decision-making. Papautsky (2023) addresses patient decision-making in high-stress environments such as surgery recovery, drawing parallels with the decision-making processes required in disaster management. In both scenarios, individuals are required to make complex, high-stakes decisions without comprehensive training or support. Ergonomics can contribute to improving decision-making by simplifying interfaces, providing real-time feedback, and using systems that account for human cognitive limitations. By doing so, disaster management systems can ensure that responders are better equipped to make quick, accurate decisions, thereby reducing the likelihood of errors.

Human factors in disaster ergonomics also encompass the design of environments that minimize stress and cognitive overload. The work of Webster and Haut (2023) on ergonomics in operating rooms is highly relevant to disaster management settings, where the physical and cognitive demands on responders are similarly high. They suggest that ergonomic improvements, such as optimizing equipment positioning and reducing visual clutter, can significantly enhance performance and reduce the risk of injury. Applying these principles to disaster management can lead to more efficient and safer operations, as responders are better able to focus on their tasks without being hindered by poorly designed environments or tools.

The role of ergonomics in enhancing team performance during disasters is another area of growing interest. The study by Willett and Demir (2023) on cognitive load and advice compliance in urban search and rescue tasks provides valuable insights into how teams can be supported through ergonomic interventions. Their research suggests that providing real-time, actionable feedback can improve compliance with safety protocols and enhance overall team performance. In disaster scenarios, where teamwork is essential, ergonomic interventions that reduce cognitive load and improve communication can lead to more effective and coordinated responses, ultimately saving lives and reducing the impact of the disaster.

Ergonomics also plays a crucial role in post-disaster recovery efforts, where the physical and psychological toll on workers can be significant. Gholami et al. (2022) highlight the importance of assessing the physical ergonomics of teleoperation interfaces used in remote disaster response tasks. Their quantitative evaluation of human body configurations during teleoperation tasks emphasizes the need for ergonomic designs that minimize physical discomfort and fatigue. In post-disaster recovery, where remote operations such as search and rescue or infrastructure repair may be conducted, ensuring that teleoperation systems are ergonomically optimized can enhance the efficiency and well-being of workers.

Moreover, disaster ergonomics must account for the diverse populations affected by disasters, including the elderly and disabled, who may have unique needs during evacuation and recovery processes. Xiao et al. (2022) discuss the hazards faced by older adults during hospital discharge, emphasizing the need for systems that are designed to accommodate the physical and cognitive limitations of vulnerable populations. In disaster scenarios, where rapid evacuation and access to medical care are critical, ergonomic designs that cater to the needs of these populations can ensure that they receive timely and appropriate assistance.

The integration of technology into disaster ergonomics is another area with significant potential. Banerjee et al. (2022) explore the use of augmented and virtual reality (AR/VR) in enhancing human performance in complex environments. These technologies can be used in disaster management training, allowing responders to simulate disaster scenarios and practice their responses in a controlled environment. The ability to simulate high-pressure situations can improve preparedness and reduce the cognitive load during actual disaster events. Furthermore, AR/VR technologies can be used in real-time during disaster response to provide responders with critical information, such as hazard locations or evacuation routes, thereby enhancing situational awareness and decision-making.

In conclusion, disaster ergonomics represents a crucial intersection of human factors and disaster management, offering solutions to the escalating challenges posed by natural and human-made disasters. By optimizing human-system interaction, improving decision-making processes, and designing environments and tools that account for human physical and cognitive limitations, ergonomics can significantly enhance the effectiveness and safety of disaster management systems. The work of researchers such as Botti et al. (2023), Papautsky (2023), Webster and Haut (2023), Willett and Demir (2023), and Gholami et al. (2022) provides valuable insights into how ergonomic principles can be applied to disaster scenarios, ultimately leading to better outcomes for both responders and affected populations. Future research should continue to explore the potential of emerging technologies, such as exoskeletons and AR/VR, in supporting disaster response efforts, while also considering the unique needs of vulnerable populations.

7. FUTURE DIRECTIONS

Human-centered ergonomics is a critical area of study, especially in industrial and occupational settings, where optimizing human performance and well-being is essential. The evolving nature of technology and its integration into work environments has created new challenges, while also offering opportunities for improvement in safety, efficiency, and user satisfaction. To chart the future course of research in this field, a thorough examination of existing gaps and thoughtful recommendations for future work is necessary.

One significant gap in current ergonomics research is the incomplete understanding of how technology-driven interfaces affect human operators. For example, Kim et al. (2023) highlighted that extended reality (XR) technologies are increasingly being used to support industrial and occupational tasks, but the ergonomic implications of such systems remain underexplored. XR systems, such as virtual and augmented reality, can potentially enhance human-computer interaction by simulating real-world scenarios. However, the long-term cognitive and physical effects of using these immersive technologies on workers need further investigation, especially in terms of fatigue, musculoskeletal issues, and cognitive load. Future research should focus on developing ergonomic guidelines tailored to XR environments to optimize user experience and minimize potential health risks.

In a similar vein, the importance of cognitive ergonomics in managing complex work systems has been stressed in various studies. Rajesh, Kumaravel, and Duffy (2023) emphasized the role of cognitive ergonomics in transportation, where human factors play a vital role in safety and efficiency. The increasing use of automation and human-computer interaction in transportation systems introduces new challenges, particularly in terms of how humans interact with these automated systems. Distracted driving, physical fatigue, and mental workload are critical issues that need to be addressed through ergonomic design improvements. While significant progress has been made, future studies should delve deeper into optimizing the human-technology interface to reduce cognitive strain and improve safety outcomes.

Furthermore, the integration of ergonomics in the design of safety-critical environments, such as cockpits and medical operating rooms, underscores the need for more comprehensive performance evaluation techniques. Brighton and Klaus (2023) conducted a review of cockpit performance evaluation metrics and noted the absence of a holistic metric that considers both ergonomic and cognitive factors. Although some subsystems, such as human-computer interaction and data management, have been evaluated separately, a unified approach that considers the overall system performance is lacking. To address this gap, future research should develop integrated evaluation frameworks that take into account the interdependencies of various cockpit subsystems. Such frameworks should also include user feedback to ensure that the design of these systems aligns with operator needs and capabilities.

Another emerging area in ergonomics research is the impact of human factors on health and safety in physically demanding professions. Edelman et al. (2022) conducted a narrative review of non-technical skills and human factors in airway management, revealing that human factors associated with work systems and processes were more prominent than user outcomes in current guidelines. The review suggests that while human factors are well-represented in the guidelines, there is still room for improvement in their application to clinical settings. Future studies should aim to bridge this gap by focusing on user-centered ergonomic interventions that prioritize healthcare workers' physical and mental well-being. This is particularly relevant given the high incidence of work-related musculoskeletal disorders (WMSDs) in physically demanding professions like healthcare and aviation maintenance (Mahmood et al., 2022).

Technological advancements in industrial ergonomics, particularly the use of digital twins (DTs) and human-robot interaction (HRI), have opened new avenues for improving worker safety and productivity. Berti and Serena (2022) examined the role of digital twins in manufacturing and logistics systems, where they are increasingly being used to simulate and optimize work processes. However, the application of DTs to assess ergonomics, mental workload, and posture feedback remains underdeveloped. Future research should focus on enhancing the capabilities of DTs to provide real-time ergonomic feedback to workers, thereby improving their safety and overall well-being. This approach could be extended to include adaptive systems that adjust work environments based on individual worker needs and capabilities, as demonstrated by Villani et al. (2022) in their study of adaptive interaction systems for inclusive workplaces.

Moreover, the study of work-related musculoskeletal disorders (WMSDs) in physically demanding occupations remains a critical area for future research. The research by Mahmood et al. (2022) on aviation maintenance workers in Pakistan highlights the significant impact of work demands on the prevalence of WMSDs. Their findings suggest that ergonomic interventions, such as task sharing and job rotation, could mitigate the risk of WMSDs in high-demand jobs. However, future studies should also explore the role of technology, such as wearable sensors and digital monitoring tools, in tracking and preventing the onset of WMSDs in real-time.

8. CONCLUSION

In conclusion, human-centered ergonomics is a dynamic and rapidly evolving field that plays a crucial role in industrial and occupational settings. As industries continue to integrate advanced technologies, particularly in the context of Industry 4.0 and 5.0, the importance of ergonomics in optimizing human-machine interactions has become increasingly evident. The advancements in motion capture, virtual reality, adaptive autonomy, and collaborative robots are reshaping the way work environments are designed and how workers interact with machines. These technologies, when combined with ergonomic principles, offer immense potential to improve both worker well-being and productivity. However, these innovations also bring new challenges. As highlighted, the aging workforce is a critical concern, requiring targeted ergonomic interventions to address the physical and cognitive decline associated with aging. Ergonomics must evolve to ensure that older workers can continue to contribute effectively in technologically advanced environments without risking their health. This includes the development of assistive technologies, such as exoskeletons, and the adaptation of work processes to reduce physical strain and cognitive overload. The application of ergonomics in non-traditional industrial settings, such as forestry and waste management, further demonstrates its broad relevance. Ergonomic interventions, whether through task redesign, improved tools, or mechanization, have proven to be essential in mitigating the risks of musculoskeletal disorders and other health issues in physically demanding jobs. Moreover, cognitive ergonomics is becoming increasingly important as industries adopt more complex automated systems. By addressing the mental demands placed on workers, ergonomic designs can help prevent cognitive overload, reduce errors, and improve overall system efficiency. Sustainability is another area where ergonomics is making significant contributions. Green ergonomics, which integrates environmental considerations into ergonomic design, is becoming a key factor in creating more sustainable manufacturing processes. By optimizing energy consumption, reducing waste, and designing more efficient work systems, ergonomics helps industries balance worker health with environmental responsibility. This is particularly relevant in the context of Industry 5.0, where human-centered approaches are essential for achieving both sustainability and industrial growth. Looking forward, the future of human-centered ergonomics will be shaped by emerging technologies and the need to address new challenges, such as the growing complexity of human-machine interactions and the demands of an aging workforce. Research into areas like extended reality, digital twins, and adaptive autonomy will play a pivotal role in developing ergonomic solutions that are both innovative and practical. Moreover, the focus on cognitive ergonomics will become increasingly important as workers are required to interact with more complex systems.

REFERENCES

[1] Alves, J., Lima, T.M., & Gaspar, P.D. (2024). The sociodemographic challenge in human-centred production systems–a systematic literature review. Theoretical Issues in Ergonomics Science, 25(1), 44–66.

[2] Attia, E.-A., Sobhi, N., Alarjani, A., & Karam, A. (2023). Improving electric motor assembly using one piece flow, ergonomics, and cellular layout. International Journal of Simulation Modelling, 22(2), 255–266.

[3] Berti, N., & Serena, F. (2022). Digital twin and human factors in manufacturing and logistics systems: State of the art and future research directions. IFAC-PapersOnLine, 55(10), 1893–1898.

[4] Botti, L., Melloni, R., Oliva, M., Perini, M., & Bacchetta, A.P. (2023). Exoskeletons to support manual material handling at work: A preliminary study. Lecture Notes in Mechanical Engineering, 833-841.

[5] Brighton, E.M., & Klaus, D.M. (2023). Categorization of select cockpit performance evaluation techniques. Aerospace Medicine and Human Performance, 94(9), 696–704.

[6] Degli Esposti, A., Magrini, C., & Bonoli, A. (2023). Door-to-door waste collection: A framework for the socio-economic evaluation and ergonomics optimisation. Waste Management, 156, 130–138.

[7] Dovramadjiev, T., Dobreva, D., & Zlateva, R. (2024). Improving the visual ergonomics of computerised workplaces through the use of specialised eye-rest software. Communications in Computer and Information Science, 2198 CCIS, 187-198.

[8] Edelman, D.A., Duggan, L.V., Lockhart, S.L., Marshall, S.D., Turner, M.C., & Brewster, D.J. (2022). Prevalence and commonality of non-technical skills and human factors in airway management guidelines: A narrative review of the last 5 years. Anaesthesia, 77(10), 1129–1136.

[9] Fadden, S. (2024). Trauma resuscitation and the damage control approach. Surgery (United Kingdom), 42(7), 479-486.

[10] Gabrielson, A.T., & Wei, J. (2024). Assessment of musculoskeletal pain and surgical ergonomic parameters among members of the American Society of Pediatric Otolaryngology. International Journal of Pediatric Otorhinolaryngology, 176, art. no. 111765.

[11] Gervasi, R., Capponi, M., Mastrogiacomo, L., & Franceschini, F. (2023). Manual assembly and Human–Robot Collaboration in repetitive assembly processes: a structured comparison based on human-centered performances. International Journal of Advanced Manufacturing Technology, 126(3-4), 1213-1231.

[12] , M., De Momi, E., & Ajoudani, A. (2022). Quantitative physical ergonomics assessment of teleoperation interfaces. IEEE Transactions on Human-Machine Systems, 52(2), 169-180.

[13] Hauptman, A.I., Flathmann, C., & McNeese, N.J. (2024). Adapting to the human: A systematic review of a decade of human factors research on adaptive autonomy. Applied Ergonomics, 120, 104336.

[14] He, Q., Li, L., Li, D., Peng, T., Zhang, X., Cai, Y., Zhang, X., & Tang, R. (2024). From Digital Human Modeling to Human Digital Twin: Framework and Perspectives in Human Factors. Chinese Journal of Mechanical Engineering (English Edition), 37(1), art. no. 9.

[15] Jakobsen, L. S., de Zee, M., Samani, A., Desbrosses, K., & Madeleine, P. (2023). Biomechanical changes, acceptance, and usability of a passive shoulder exoskeleton in manual material handling. Applied Ergonomics, 113, 104104.

[16] Kim, K., Marques, B., Jeong, H., Silva, S., Cho, I., Ferreira, C., Kim, H., Dias, P., Jeon, M., & Santos, B.S. (2023). An overview of the 2nd international workshop on extended reality for industrial and occupational supports (XRIOS). Proceedings - 2023 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops, VRW 2023, 364–369.

[17] Kirkici, H., Colim, A., Carneiro, P., & Pedrosa, P. (2024). Development of a questionnaire to understand future users' preferences about human-centric autonomous car interior. Studies in Systems, Decision and Control, 492, 109–116.

[18] Lagomarsino, M., Lorenzini, M., Balatti, P., Momi, E.D., & Ajoudani, A. (2023). Pick the right co-worker: Online assessment of cognitive ergonomics in human-robot collaborative assembly. IEEE Transactions on Cognitive and Developmental Systems, 15(4), 1928–1937.

[19] Landekić, M., Bačić, M., Pandur, Z., Bakarić, M., Šporčić, M., & Nakić, J. (2023). Kinematic analysis of the forestry workers' upper body during chainsaw starting activity. Forests, 14(12), art. no. 2427.

[20] Mahendran, V., Turpin, L., Boal, M., & Francis, N.K. (2024). Assessment and application of non-technical skills in robotic-assisted surgery: a systematic review. Surgical Endoscopy, 38(4), 1758-1774.

[21] Mahmood, M., Naseem, A., Ahmad, Y., & Mirza, M.Z. (2022). Work demand and prevalence of work-related musculoskeletal disorders: A case study of Pakistan aviation maintenance workers. IEEE International Conference on Industrial Engineering and Engineering Management, 324–328.

[22] Matib, M., Bouhadiba, B., & Lounis, Z. (2023). A case study on the implementation of a technological ergonomic design in oil and gas facilities. Environmental Engineering and Management Journal, 22(12), 2093-2107.

[23] Mohamad, M.F., Sowat, S.N., Selamat, H., Azaman, A., & Harith, H.H. (2023). Structural design of a passive wearable exoskeleton to assist oil palm harvesting operation. Journal of Oil Palm Research, 35(4), 653–667.

[24] Montini, E., Ploner, G., Matteri, D., Cutrona, V., Rocco, P., Bettoni, A., & Pedrazzoli, P. (2024). Impact of collaborative robots on human trust, anxiety, and workload: Experiment findings. IFIP Advances in Information and Communication Technology, 729 IFIP, 401–415.

[25] Nadaffard, A., Oliveri, L.M., D'Urso, D., Facchini, F., & Sassanelli, C. (2024). Exploring the cognitive workload assessment according to human-centric principles in Industry 5.0. IFIP Advances in Information and Communication Technology, 729 IFIP, 457–469.

[26] Neri, F., Laschi, A., Bertuzzi, L., Galipò, G., Frassinelli, N., Fabiano, F., Marchi, E., Foderi, C., & Marra, E. (2023). A comparison between the latest models of Li-Ion batteries and petrol chainsaws assessing noise and vibration exposure in cross-cutting. Forests, 14(5), 898.

[27] Papautsky, E.L. (2023). Patient decision making in recovering from surgery. Frontiers in Psychology, 14, art. no. 1170658.

[28] Pereira, A. C., Alves, A. C., & Arezes, P. (2023). Augmented reality in a lean workplace at smart factories: A case study. Applied Sciences (Switzerland), 13(16), 9120.

[29] Poje, A., Lipužič, B., Bilobrk, I., & Pandur, Z. (2024). Time composition, efficiency, workload, and noise exposure during tree felling and processing with petrol and battery-powered chainsaws in mixed high forest stands. Forests, 15(5), 798.

[30] Prunet, T., Absi, N., Borodin, V., & Cattaruzza, D. (2024). Optimization of human-aware logistics and manufacturing systems: A comprehensive review of modeling approaches and applications. EURO Journal on Transportation and Logistics, 13, 100136.

[31] Rajesh, A., Kumaravel, K., & Duffy, V.G. (2023). Ergonomics in transportation: A comprehensive review and analysis. Lecture Notes in Computer Science, 14057 LNCS, 130–144.

[32] Real, C., & Torres, Y. (2024). Effect of changes in the sequence of assembly operations on error rates: A case study from the car manufacturing industry. IEEE Access, 12, 34644–34655.

[33] Reese, P., Hurley, R., & Cavender, G.A. (2024). Enhancing Package Ergonomics for Arthritis Consumers: A Case Study. Packaging Technology and Science, 37(8), 735-743.

[34] Staněk, L., & Mergl, V. (2024). Effect of the body mass index and length of work on the stress of individual body parts of chainsaw operators. Journal of Forest Science, 70(8), 436–445.

[35] Staněk, L., Neruda, J., & Nevrkla, P. (2023). The magnitude of fatigue recorded in individual body parts of chainsaw operators after work. Forests, 14(10), 2023.

[36] Trstenjak, M., Hegedić, M., Cajner, H., Opetuk, T., & Tošanović, N. (2024). Cognitive ergonomics in Industry 5.0. Lecture Notes in Mechanical Engineering, 763-770.

[37] Villani, V., Sabattini, L., Zanelli, G., Callegati, E., Bezzi, B., Barańska, P., Mockałło, Z., Zołnierczyk-Zreda, D., Czerniak, J.N., Nitsch, V., Mertens, A., & Fantuzzi, C. (2022). A user study for the evaluation of adaptive interaction systems for inclusive industrial

workplaces. IEEE Transactions on Automation Science and Engineering, 19(4), 3300–3310.

[38] Webster, K.L.W., & Haut, E.R. (2023). Human factors and ergonomics in the operating room. Handbook of Perioperative and Procedural Patient Safety, 75-86.

[39] Willett, M.M., & Demir, M. (2023). Understanding the impact of team cognitive load and advice compliance in urban search and rescue tasks. Proceedings of the Human Factors and Ergonomics Society, 67(1), 2484-2489.

[40] Yasue, N., Mahmoodi, E., Zúñiga, E.R., & Fathi, M. (2025). Analyzing resilient performance of workers with multiple disturbances in production systems. Applied Ergonomics, 122, art. no. 104391.

[41] Zarei, E., Khan, F., & Abbassi, R. (2023). How to account artificial intelligence in human factor analysis of complex systems? Process Safety and Environmental Protection, 171, 736-750.

[42] Zigart, T., Zafari, S., Stürzl, F., Kiesewetter, R., Kasparick, H.-P., & Schlund, S. (2023). Multi-assistance systems in manufacturing - a user study evaluating multi-criteria impact in a high-mix low-volume assembly setting. Computers and Industrial Engineering, 186, art. no. 109674.