Malaysian Journal of Ergonomics (MJEr)
Volume Number Issue Year [42-54]

Recent Advances in Ergonomic Studies on Material Handling: Mitigating Musculoskeletal Risks and Enhancing Worker Safety

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

[1] Fakulti Kejuruteraan & Teknologi Mekanikal, Universiti Malaysia Perlis
Date Received : 20 Oct 2024, Date Revised: 26 Dis 2024, Date Accepted: 30 Dis 2024

ABSTRACT

Manual material handling (MMH) tasks are a significant contributor to work-related musculoskeletal disorders (WMSDs), particularly in industries where repetitive motions, awkward postures, and excessive loads are common. Recent advances in ergonomic interventions aim to mitigate these risks, enhancing worker safety and reducing the incidence of injuries. The integration of automation technologies, such as robotic assistants and human-machine interfaces, has proven effective in reducing human involvement in monotonous tasks, thereby alleviating physical strain. Additionally, passive back-support exoskeletons have emerged as promising tools to provide mechanical support during heavy lifting, bending, and repetitive movements, effectively reducing musculoskeletal risks. Technological innovations, including wearable sensors and AI-driven tools, have further improved ergonomic assessments by providing real-time monitoring and feedback on workers' posture and movements. These advancements allow for timely adjustments and preventive measures, ensuring a safer and more efficient working environment. However, challenges remain regarding the long-term effects and user acceptance of exoskeletons and other ergonomic interventions. Studies also highlight the importance of ergonomic risk assessments, utilizing tools such as the Rapid Entire Body Assessment (REBA) and fuzzy logic models to identify and mitigate high-risk tasks.

Keywords: manual material handling, work-related musculoskeletal disorders, exoskeletons, ergonomic risk assessment, automation, wearable sensors, worker safety

1. INTRODUCTION

Manual material handling (MMH) tasks in industrial settings are a significant contributor to work-related musculoskeletal disorders (WMSDs), with studies indicating that a large proportion of workers engaged in MMH tasks experience injuries over time (Anwer et al., 2021). WMSDs are particularly prevalent in industries where repetitive tasks, awkward postures, and excessive loads are common. Ergonomic interventions, including technology advancements and the application of proper risk assessment methods, have been shown to reduce the physical strain on workers and mitigate the risks of WMSDs.

Recent technological innovations have been increasingly employed to alleviate the risks associated with repetitive MMH tasks. Automation technologies, such as kinesthetic teaching systems for laboratory micropipetting tasks, aim to reduce human involvement in monotonous procedures, thereby decreasing ergonomic risks (Rocha et al., 2022). By automating such tasks, particularly those requiring fine motor skills, operators can be redirected toward non-repetitive activities, thus lowering the likelihood of wrist musculoskeletal disorders. Similarly, in industrial settings, robotic systems and human-machine interfaces offer potential in improving the flexibility and usability of such automated systems, making their integration into various work environments easier.

Industrial exoskeletons have also gained attention as a promising ergonomic intervention to reduce the burden of MMH tasks. Passive back-support exoskeletons, for instance, provide mechanical support to workers without relying on power sources, which makes them more accessible for practical applications in various industries (Madinei et al., 2022). The use of such exoskeletons is designed to alleviate physical loads, especially in tasks involving repetitive trunk flexion and extension. Recent studies have demonstrated the potential of these devices to generate assistive torque during dynamic and static postures, reducing the physical strain on the back muscles and decreasing the risk of WMSDs in workers who perform frequent bending and lifting activities.

Several studies highlight the importance of risk assessments in managing the ergonomic conditions of MMH tasks. One study focused on construction workers found that awkward postures, manual handling, prolonged work periods, and high job demands significantly increased the odds of developing WMSDs (Anwer et al., 2021). For example, manual lifting and bending movements were shown to exert substantial strain on the lower back, resulting in high rates of back pain and other musculoskeletal injuries among workers. The application of ergonomic risk assessment tools, such as the Rapid Entire Body Assessment (REBA), provides insight into the severity of postural risks associated with various MMH activities, emphasizing the need for ergonomic interventions to prevent these injuries (Chen, 2024).

Fuzzy logic models have emerged as an effective decision-support system for evaluating the ergonomic risks involved in MMH tasks (Contreras-Valenzuela et al., 2022). By incorporating variables such as time duration, weight limits, and repetitiveness, fuzzy logic can replicate ergonomic evaluations with a high degree of precision, as validated against ISO standards. This approach has proven to be useful for automating risk evaluations in different work environments, helping to identify high-risk tasks and implement timely corrective actions.

One of the challenges associated with implementing ergonomic interventions in industries is the manual handling of large and awkwardly shaped materials, such as waste containers. The manual handling of waste has been identified as a high-risk activity, particularly in door-to-door waste collection systems, where workers frequently lift and carry heavy bins. Research conducted in this area suggests that increasing bin capacity and introducing mechanized collection systems could significantly reduce the ergonomic risks faced by waste collection workers, leading to improved worker safety and performance (Degli Esposti et al., 2023).

Wearable sensor technologies have shown significant potential in automating ergonomic assessments for MMH tasks, particularly for monitoring low back disorders (Nurse et al., 2023). Sensors such as inertial measurement units (IMUs) and pressure insoles can be combined with machine learning algorithms to provide real-time feedback on workers' postures and motions. The data collected from these sensors can be used to assess WMSD risks more accurately, allowing for better prevention strategies. Studies show that while trunk motion data alone may not provide strong correlations with WMSD risks, combining it with force data from pressure insoles can yield highly accurate estimates of injury risks during MMH tasks.

Despite the benefits of new technologies, ergonomic interventions must also consider the social and organizational challenges that arise with their implementation. The introduction of automated guided vehicles (AGVs) in production facilities, for instance, requires changes to work procedures and employee training. A failure to address these human and organizational aspects may hinder the effectiveness of such interventions, as employees must adapt to new workflows and develop trust in the technology (Thylén et al., 2023). Therefore, successful ergonomic interventions need to balance the technical and human factors to optimize worker safety and performance.

Finally, the effectiveness of exoskeletons in supporting MMH tasks has been further validated through practical studies. Preliminary investigations into the use of back-support exoskeletons in industrial settings reveal that these devices can effectively reduce physical strain during manual lifting tasks, particularly by lowering the risk of back injuries (Botti et al., 2023). However, concerns remain about the long-term effects of exoskeleton use, as well as the potential for discomfort or injury if the devices are not appropriately fitted to the user. Continued research is necessary to explore the full range of benefits and limitations associated with exoskeleton technology in MMH applications.

2. Recent Technological Innovations in Ergonomic Material Handling

Recent technological innovations have played a vital role in mitigating the ergonomic risks associated with material handling tasks. Automation of repetitive tasks, robotic assistants, exoskeletons, and wearable technologies have all contributed significantly to improving worker safety and reducing the incidence of musculoskeletal disorders (MSDs). These advancements have been particularly effective in industries where manual material handling is unavoidable, providing practical solutions to minimize ergonomic risks.

The introduction of kinesthetic teaching systems and similar technologies in automating repetitive tasks is a key development in this area. These systems are especially useful in environments such as laboratories, where tasks like micropipetting are both repetitive and physically taxing on workers. The automation of such procedures helps redirect workers to less monotonous tasks, thereby reducing the risk of musculoskeletal injuries, particularly in the wrist (Rocha et al., 2022). The implementation of these systems allows for greater flexibility in the workplace, making it easier to adapt to different tasks while improving overall ergonomic conditions.

In the construction and manufacturing sectors, robotic assistants and exoskeletons have emerged as promising tools to reduce the physical burden on workers engaged in material handling. Back-support exoskeletons, for instance, provide mechanical support to workers during lifting tasks, reducing the physical strain on the lower back. A study demonstrated that passive exoskeletons, such as the BackX™ AC and Laevo™ V2.5 models, can effectively mitigate the risk of back injuries by improving trunk stability and reducing the physical demands of repetitive lifting tasks (Madinei et al., 2021). Another study using a vision-based pose estimation algorithm showed that these exoskeletons reduced workers' ergonomic risk by 31.7% during material handling tasks by correcting awkward postures (Liu et al., 2024). These findings suggest that exoskeletons can significantly reduce the risk of work-related musculoskeletal disorders in industries where heavy lifting is a regular occurrence.

However, despite these benefits, there are concerns about the long-term use of exoskeletons, particularly regarding their impact on neuromuscular control. Research has shown that while exoskeletons improve ergonomic conditions during repetitive tasks, they may also compromise trunk coordination, leading to potential unintended consequences for the wearer's overall motor control (Madinei et al., 2021). This highlights the importance of selecting the appropriate type of exoskeleton based on the specific requirements of the task and the user's physical condition.

The integration of wearable technology, such as sensors and AI-driven tools, further enhances the ability to monitor and manage ergonomic risks in real-time. Wearable sensors, such as inertial measurement units (IMUs), have been used to track workers' posture and movement during manual material handling tasks. These devices provide real-time feedback, allowing for immediate adjustments to reduce the risk of injury (Humadi et al., 2021). Studies comparing wearable sensors with optical technologies, such as the Kinect V2, have shown that IMUs offer more reliable and accurate assessments of ergonomic risks in field settings, making them an ideal choice for in-field ergonomic risk assessments (Humadi et al., 2021). Wearable sensors combined with AI can also predict potential risks by analyzing workers' movements and workloads, offering proactive solutions to prevent injuries.

Moreover, the use of smart tools and devices like ring scanners and smart glasses in warehouse settings has proven beneficial for both productivity and worker comfort. Ring scanners, in particular, have been identified as the most comfortable and efficient wearable devices for scanning tasks, reducing the physical strain associated with handling handheld devices (Gaddis et al., 2022). However, smart glasses, while technologically advanced, have been reported to cause discomfort in the eyes, neck, and shoulders over time, indicating the need for further refinement before they can be widely adopted in material handling tasks (Gaddis et al., 2022).

In addition to wearable technology, hybrid order-picking systems (HOPS) that integrate human and robotic collaboration have been developed to reduce the ergonomic risks associated with repetitive tasks in warehouses. These systems allow robots and humans to work together, with robots handling the more physically demanding aspects of the job while humans focus on tasks that require fine motor skills. Studies have shown that these systems can reduce operational costs and the daily workload of human workers, although attention must be paid to the weight of items being handled to prevent an increase in the frequency of lifting activities (Zhang et al., 2023).

Another area where wearable technology and robotics are making significant strides is in virtual reality (VR) simulations. These simulations allow workers to experience the benefits and limitations of using exoskeletons in a controlled virtual environment. By simulating different lifting tasks and showing the potential biomechanical risks and benefits associated with exoskeleton use, these VR programs help workers and managers make informed decisions about adopting such technologies in real-world settings (Park et al., 2024). The use of VR in this context not only enhances worker safety but also promotes a better understanding of how these technologies can be optimized for specific tasks.

3. Impact of Manual Material Handling on Worker Health

Manual material handling (MMH) tasks, common in industries such as construction, nursing, and logistics, have been closely linked to work-related musculoskeletal disorders (WMSDs). These disorders primarily affect the back, shoulders, neck, and upper limbs, resulting in pain and disability, which can significantly impact worker productivity and overall well-being. Research indicates that WMSDs are prevalent in high-risk occupations due to the physical demands involved, such as lifting, lowering, pushing, pulling, and handling heavy loads. For instance, studies have consistently shown a high prevalence of musculoskeletal pain and discomfort among workers engaged in MMH, with back pain being particularly common (Rajendran et al., 2021).

Workers in sectors such as construction and nursing face a high risk of developing WMSDs due to the repetitive and physically demanding nature of their jobs. In construction, manual handling of heavy materials and tools often leads to awkward postures, exerting excessive strain on the musculoskeletal system. Research in construction environments has revealed that tasks involving repetitive lifting, especially with awkward postures, substantially increase the risk of musculoskeletal injuries (Shin & Jeong, 2022). Similarly, in healthcare, nursing staff frequently engage in tasks that involve moving patients, often without the aid of mechanical lifting devices, which contributes to an elevated risk of back injuries and WMSDs (Davoudi Kakhki et al., 2024).

Multiple risk factors contribute to the development of WMSDs in occupations that rely heavily on manual material handling. Physical factors such as awkward postures, repetitive movements, and manual handling of heavy loads have been identified as key contributors to these disorders. Ergonomic evaluations using tools such as the Rapid Entire Body Assessment (REBA) and the National Institute for Occupational Safety and Health (NIOSH) Lifting Equation are commonly used to assess the physical demands of these tasks. Research has shown that these methods can effectively identify tasks that place workers at a high risk for musculoskeletal injuries, allowing for the implementation of preventive measures (Adhaye & Jolhe, 2023).

In addition to physical risk factors, psychosocial factors also play a crucial role in the development of WMSDs. Psychosocial stressors such as time pressure, low job satisfaction, and lack of control over work tasks can exacerbate physical strain and increase the risk of injury. Studies have highlighted the relationship between mental stress and musculoskeletal pain, particularly in high-risk occupations like logistics and healthcare. Workers experiencing high levels of stress are more likely to report musculoskeletal pain, suggesting that both physical and psychosocial factors must be considered when addressing ergonomic risks (Shin & Jeong, 2022). The interaction between physical and mental stress highlights the need for comprehensive ergonomic interventions that address both the physical and psychosocial aspects of work.

Ergonomic interventions, such as the redesign of tasks and the introduction of assistive technologies like exoskeletons, have been shown to reduce the incidence of WMSDs. Exoskeletons, in particular, have been effective in reducing the physical load on workers by providing mechanical support to the body during lifting and carrying tasks. For example, studies on passive back-support exoskeletons have demonstrated their ability to reduce perceived physical exertion and improve ergonomic safety in material handling tasks (Davoudi Kakhki et al., 2024). Additionally, the use of ergonomic tools like exoskeletons can lead to lower muscle activation and reduced physical discomfort in the back, shoulders, and knees, thus mitigating the risk of musculoskeletal injuries (Schrøder Jakobsen et al., 2023).

In occupations such as farming, where workers are often exposed to harsh physical conditions and ergonomic hazards, musculoskeletal disorders are prevalent. A study of older female farmers, for example, found that awkward postures, repetitive movements, and manual handling tasks were significant contributors to musculoskeletal pain, particularly in the upper and lower limbs (Shin & Jeong, 2022). The study also highlighted the importance of addressing both ergonomic and environmental factors to reduce the risk of injury in this population.

The introduction of ergonomic tools and assessments has also proven effective in evaluating and mitigating the risk of musculoskeletal injuries in various industries. For instance, the use of the NIOSH Lifting Equation and the Ovako Working Posture Assessment System (OWAS) in evaluating manual handling tasks in a food warehouse revealed that nearly 94% of workers experienced moderate to severe discomfort in the ankle, knee, and lower back due to the physically demanding nature of the work. Recommendations for task redesign and the use of auxiliary devices to assist in lifting and carrying tasks were proposed to reduce the risk of injury (Adhaye & Jolhe, 2023).

Despite the effectiveness of ergonomic tools and interventions, there is still a need for further research on how to best implement these solutions in real-world settings. While tools such as exoskeletons have shown promise in reducing the physical demands of manual material handling tasks, concerns remain about their long-term use and acceptance by workers. A study on the use of passive shoulder exoskeletons in logistics revealed that while the exoskeletons reduced muscle activity and perceived effort, the workers' emotions towards using the exoskeletons decreased over time, raising questions about their suitability for long-term use in certain industries (Schrøder Jakobsen et al., 2023).

4. Assessment Tools and Methods in Ergonomic Risk Evaluation

In the field of ergonomic risk evaluation, a variety of assessment tools and methods have been developed to address the physical demands of manual material handling (MMH) tasks and reduce the incidence of work-related musculoskeletal disorders (WMSDs). Ergonomic risk assessment tools, such as the Rapid Entire Body Assessment (REBA) and the Rapid Upper Limb Assessment (RULA), are widely used to evaluate the physical postures of workers during MMH tasks. These tools aim to identify awkward or hazardous postures that can contribute to musculoskeletal strain and injury. Both REBA and RULA score postures based on their potential risk levels, allowing for an effective assessment of the ergonomic conditions in workplaces where material handling is prominent. Additionally, more advanced methods, including the incorporation of fuzzy logic interfaces, have been applied to further enhance the precision of risk assessment by considering complex and continuous movements within the human body (Bairwa et al., 2022).

A growing trend in ergonomic evaluations is the integration of computer vision and biomechanical models to complement traditional observational methods. These technologies offer significant advancements in terms of accuracy and automation. For instance, computer vision systems, combined with motion capture techniques, allow for real-time tracking of workers' movements, providing detailed data on posture, joint angles, and body mechanics. This technology has the potential to significantly improve the efficiency and accuracy of ergonomic assessments by minimizing human error in observational studies (Wang et al., 2023). Biomechanical models, on the other hand, enable a more detailed understanding of the physical forces acting on the body during MMH tasks. By simulating various movements and postures, these models help predict the risk of injury based on the strain placed on different body parts, particularly the lower back, shoulders, and legs (Muller et al., 2022).

Several studies have explored the efficacy of computer vision and biomechanical models in assessing the ergonomic risks associated with manual material handling. One notable example involves the use of inertial motion capture (IMC) systems, which allow for the estimation of back loading during MMH tasks without the need for force measurements. This method offers a more practical and ecologically valid approach to assessing workplace physical exposure, as it does not rely on the controlled conditions typically required in laboratory settings. IMC-based approaches have demonstrated their potential in accurately estimating L5/S1 moments, a critical factor in evaluating lower back strain during lifting tasks (Muller et al., 2022). By providing real-time feedback on body posture and mechanics, these systems can play a vital role in reducing the risk of musculoskeletal injuries in workers engaged in MMH activities.

Additionally, simulation models have gained popularity as a means of evaluating ergonomic risks in complex material handling environments. These models use computer-generated simulations to recreate workplace conditions and test various ergonomic interventions. For example, studies have used simulation-based approaches to evaluate the impact of facility layout changes on material handling efficiency and ergonomic risk. The findings from such studies suggest that the strategic redesign of workflows and facility layouts can significantly reduce ergonomic risks by minimizing unnecessary movements and improving the overall flow of materials (Iyer et al., 2023). Simulation models also allow for the testing of different intervention strategies, such as the use of assistive devices or modifications to task design, providing valuable insights into the potential effectiveness of these measures before their implementation in real-world settings.

Another important development in ergonomic risk assessment is the use of wearable sensors and IoT-enabled devices to monitor workers' physical activity and posture during MMH tasks. These devices, often integrated with computer vision systems, provide continuous data on workers' movements, enabling real-time ergonomic assessments. For example, inertial measurement units (IMUs) and surface electromyography (sEMG) sensors have been used to collect data on kinematics and muscular activity, which can then be analyzed using machine learning algorithms to assess the risk of injury and recommend corrective actions. This approach offers the advantage of continuous monitoring, allowing for the identification of high-risk activities as they occur and enabling immediate interventions to prevent injury (Bassani et al., 2021).

The integration of wearable sensors and computer vision systems represents a significant advancement in the field of ergonomic risk assessment. These technologies not only provide more accurate and detailed data but also allow for the development of personalized interventions based on the specific movements and postures of individual workers. By continuously monitoring workers' physical activity and providing real-time feedback, these systems can help reduce the risk of WMSDs and improve overall workplace safety.

5. Case Studies and Applications

Exoskeletons have become increasingly prominent in addressing ergonomic challenges, particularly in industries where manual material handling (MMH) is prevalent. The adoption of these assistive technologies is primarily aimed at reducing the physical strain experienced by workers, mitigating the risks of musculoskeletal disorders (MSDs), and enhancing overall worker safety. Back-support exoskeletons, for instance, have been tested across various industries, demonstrating their potential to reduce the activation of key muscle groups, particularly the lumbar erector spinae (LES), which plays a critical role in lower back stability during lifting tasks. A study on the application of back-support exoskeletons by Di Natali et al. (2024) introduced the "Equivalent Weight" method, highlighting the reduction in ergonomic risks during material handling tasks. This pilot study found that using the StreamEXO exoskeleton could reduce the Lifting Index by up to 64%, emphasizing the potential of exoskeletons in lowering the ergonomic risks associated with manual lifting, lowering, and carrying tasks.

In addition to back-support exoskeletons, shoulder support exoskeletons are being utilized in logistics and industrial settings to alleviate shoulder strain. For example, studies have explored the efficacy of various designs that provide assistance in overhead tasks, which are notorious for contributing to shoulder fatigue and injury. The implementation of exoskeletons in such environments has shown a notable reduction in shoulder muscle activity and perceived exertion, leading to improved ergonomics and worker comfort during repetitive tasks.

Further insights into the use of exoskeletons can be gleaned from studies evaluating passive and active designs. Kim et al. (2021) assessed the impact of an active back-support exoskeleton on workers during load-lifting tasks. This study found significant reductions in muscle activity, particularly in the LES, which underscores the ergonomic benefits of such devices. However, the study also pointed out that the usability of the exoskeleton was hindered by its weight, leading to increased time spent performing tasks and higher perceived exertion levels. This highlights the need for further optimization of exoskeleton designs to balance efficacy with user comfort and efficiency in the workplace.

On a broader scale, exoskeletons are being tested not only in logistics but also in the construction industry, where workers frequently engage in dynamic and static MMH tasks. Golabchi et al. (2022) investigated the use of passive back-support exoskeletons in construction, focusing on the rate of perceived exertion (RPE), level of discomfort, and overall fit and comfort. The study found that the exoskeleton significantly reduced discomfort in the lower back, particularly during static tasks, although some discomfort was reported in the chest area due to the design of the exoskeleton. These findings suggest that while exoskeletons can be effective in reducing back strain, their design must also consider other areas of the body to ensure a more comprehensive ergonomic solution.

The use of exoskeletons is not limited to logistics and construction; industries such as manufacturing are also exploring their potential. Sharotry et al. (2022) proposed a Digital Twin (DT) framework for detecting biomechanical fatigue in workers during MMH tasks. This approach utilizes a simulation model to analyze joint angles and detect fatigue, allowing for more personalized interventions based on the specific movements of individual workers. By incorporating exoskeletons into this framework, the DT could provide real-time feedback on the worker’s posture and assistive needs, optimizing the use of exoskeletons for fatigue management and injury prevention.

Beyond exoskeletons, automation plays a critical role in improving ergonomics, particularly in waste collection tasks. Automation of manual waste handling tasks has the potential to significantly reduce ergonomic risks by minimizing the need for workers to perform physically demanding tasks, such as lifting heavy waste bins or manually sorting through materials. By implementing automated systems, waste collection companies can optimize workflow, reduce physical strain on workers, and enhance overall safety. Automation systems that integrate robotic arms, conveyors, and automated sorting technologies have been shown to reduce the need for manual lifting and twisting, which are common contributors to MSDs in the waste management sector. Such systems not only improve worker safety but also increase the efficiency of waste collection processes, reducing the likelihood of accidents and injuries.

In waste collection, ergonomic optimizations can extend beyond automation. Studies have shown that the redesign of workstations and the implementation of ergonomically designed tools can further reduce physical strain. For example, the use of height-adjustable platforms or conveyors allows workers to handle waste at more favorable heights, minimizing the need for bending or lifting heavy loads. These modifications can lead to substantial reductions in the incidence of lower back and shoulder injuries, which are common among waste collection workers.

6. Challenges and Future Directions

Recent advancements in ergonomic research related to material handling highlight significant progress in mitigating musculoskeletal risks and improving worker safety. However, challenges persist, especially with technological limitations in implementing novel ergonomic solutions, such as exoskeletons, and the integration of advanced technologies like artificial intelligence (AI), machine learning, and robotics.

One major issue identified is the long-term impact of exoskeletons in manual material handling (MMH). Studies, such as those by Ali et al. (2021), show that while exoskeletons reduce physical strain on the spine, concerns remain regarding their comfort, user acceptance, and overall practicality in industrial settings. Exoskeletons have the potential to alleviate musculoskeletal disorders (MSDs), but further research is necessary to assess the long-term physiological impact on users. Additionally, the lack of standardized practices and guidelines for their implementation in various MMH tasks hinders widespread adoption (Ali et al., 2021). For instance, Maciukiewicz et al. (2021) found that while ergonomic interventions, such as back-support exoskeletons, effectively reduce muscle strain, the user's reluctance to wear such devices throughout the workday limits their application. Therefore, further studies are necessary to explore these aspects and address the issue of standardization across different industries.

Another challenge is the high variability in MMH tasks, which complicates the development of universal solutions. Ryu et al. (2021) pointed out that rule-based ergonomic assessments often fail to accurately predict MSD risks in tasks involving heavy manual handling. The study showed that such assessments can result in overestimated risk levels, leading to unnecessary ergonomic interventions. The lack of comprehensive biomechanical models that accurately account for the dynamic nature of MMH tasks remains a limitation. Consequently, many researchers advocate for the use of biomechanical and physiological data to supplement traditional ergonomic risk assessments (Ryu et al., 2021).

Technological limitations also extend to remote handling systems, such as those employed in radiation environments. Valenzuela et al. (2023) discussed how the IFMIF-DONES system requires significant advancements in terms of control interfaces and integration with human operators. The need for high availability and robust teleoperation systems, which are vital in radiation-heavy environments, calls for further innovation in control systems to support MMH tasks in such hazardous settings (Valenzuela et al., 2023).

Despite these limitations, there are several promising avenues for future research and development. The integration of AI and machine learning into ergonomic solutions has the potential to revolutionize MMH tasks. AI-powered systems could improve real-time risk assessments and provide personalized ergonomic recommendations based on individual workers' movements and physical capabilities. According to Conforti et al. (2020), AI and wearable sensor networks allow for more precise biomechanical overload assessments, significantly improving the safety of MMH operations. By using motion capture data and machine learning algorithms, ergonomic interventions can be tailored to specific tasks, reducing injury risks more effectively than traditional methods.

Moreover, advancements in robotics are expected to enhance worker safety in MMH tasks by reducing the need for human involvement in hazardous or physically demanding activities. Mahmud et al. (2024) explored the potential of occupational exoskeletons in construction, where robotic systems can complement human workers by taking over repetitive, heavy-lifting tasks. This synergy between humans and robots, combined with AI, could lead to a significant reduction in MSD prevalence in manual labor-intensive industries (Mahmud et al., 2024).

Opportunities for future research include the development of smart wearable technologies to monitor workers' movements and physical conditions in real-time. Kjaer et al. (2022) proposed a classification system using smart insoles to monitor lifting ergonomics, which achieved 98.8% accuracy. Such technologies could provide immediate feedback to workers, helping them adjust their movements to prevent injuries. Furthermore, this data can be fed into machine learning models to continuously improve ergonomic assessments (Kjaer et al., 2022).

7. CONCLUSION

The review of recent advances in ergonomic studies on material handling reveals significant strides in mitigating musculoskeletal risks and enhancing worker safety. These developments have been driven by the integration of emerging technologies, such as automation, wearable devices, exoskeletons, and advanced risk assessment tools. These innovations are addressing long-standing ergonomic challenges in manual material handling (MMH) tasks, offering promising solutions to reduce the prevalence of work-related musculoskeletal disorders (WMSDs). One of the key findings of this review is the positive impact of automation and robotics in MMH environments. Automated systems, like kinesthetic teaching and robotic assistants, have proven effective in reducing human involvement in repetitive, high-strain tasks, thereby decreasing the risk of WMSDs. These technologies enable workers to transition from monotonous activities to more dynamic roles, enhancing overall safety and reducing injury rates. Additionally, robotic and human-machine interfaces are becoming more flexible, allowing easier integration into various industrial settings, improving worker safety while maintaining productivity. Exoskeletons have emerged as one of the most impactful interventions, providing workers with mechanical support during physically demanding tasks such as lifting, carrying, and bending. Both passive and active exoskeletons have demonstrated potential in alleviating back strain, lowering muscle activation, and reducing the physical burden on the lumbar region during MMH tasks. However, long-term studies are required to fully understand their physiological effects, user comfort, and potential drawbacks, such as restricted movement or discomfort from poorly fitted devices. Wearable sensor technologies, particularly those combined with machine learning, are advancing real-time ergonomic risk assessments. These devices, including inertial measurement units (IMUs) and pressure sensors, provide accurate data on posture and physical movements, allowing for real-time feedback and timely corrective interventions. This capability is especially valuable in industries where repetitive and awkward postures increase the risk of WMSDs. The ability to continuously monitor worker conditions and adjust interventions accordingly represents a significant leap in ergonomic injury prevention. Despite these technological advancements, several challenges persist in optimizing ergonomic interventions. Issues related to the long-term usability of exoskeletons, concerns about their impact on worker comfort, and the variability of tasks across industries highlight the need for continued research. Additionally, the integration of these new technologies often requires adjustments in workplace culture and workflows, which may encounter resistance from workers unaccustomed to automated or assisted labor systems. Looking ahead, future research must focus on enhancing the ergonomics of MMH tasks by refining existing technologies and developing new solutions. The potential for artificial intelligence and machine learning to personalize ergonomic interventions based on individual worker data is promising. These advancements could improve the precision of risk assessments and interventions, making ergonomic tools more efficient and accessible to diverse industries. Moreover, continued efforts to standardize ergonomic tools, particularly exoskeletons, are essential for their broader adoption and practical application.

REFERENCES

[1] Adhaye, A. M., & Jolhe, D. A. (2023). Ergonomic assessment for designing manual material handling tasks at a food warehouse in India: A case study. Human Factors and Ergonomics In Manufacturing, 33(6), 499-520. https://doi.org/10.1002/hfm.21004

[2] Ali, A., Fontanari, V., Schmoelz, W., & Agrawal, S. K. (2021). Systematic review of back-support exoskeletons and soft robotic suits. Frontiers in Bioengineering and Biotechnology, 9, 765257. https://doi.org/10.3389/fbioe.2021.765257

[3] Anwer, S., Li, H., Antwi-Afari, M.F., & Wong, A.Y.L. (2021). Associations between physical or psychosocial risk factors and work-related musculoskeletal disorders in construction workers based on literature in the last 20 years: A systematic review. International Journal of Industrial Ergonomics, 83, 103113. https://doi.org/10.1016/j.ergon.2021.103113

[4] Bairwa, R. C., Jain, R., Meena, M. L., & Rana, K. B. (2022). Physiological evaluation of normal and inclined walking in unorganized sector workers. Lecture Notes in Mechanical Engineering, 231-236. https://doi.org/10.1007/978-981-16-9236-9_21

[5] Bassani, G., Filippeschi, A., & Avizzano, C. A. (2021). A dataset of human motion and muscular activities in manual material handling tasks for biomechanical and ergonomic analyses. IEEE Sensors Journal, 21(21), 24731-24739. https://doi.org/10.1109/JSEN.2021.3113123

[6] 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. https://doi.org/10.1007/978-3-031-34821-1_91

[7] Contreras-Valenzuela, M.R., Seuret-Jiménez, D., Hdz-Jasso, A.M., Hernández, V.A.L., Abundes-Recilla, A.N., & Trutié-Carrero, E. (2022). Design of a fuzzy logic evaluation to determine the ergonomic risk level of manual material handling tasks. International Journal of Environmental Research and Public Health, 19(11), 6511. https://doi.org/10.3390/ijerph19116511

[8] Davoudi Kakhki, F., Moghadam, A., Nieto, A., & Vora, H. (2024). Evaluating the efficacy of a passive exoskeleton for enhancing ergonomics in manufacturing. Applied Sciences (Switzerland, 14(13), 5810. https://doi.org/10.3390/app14135810

[9] 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. https://doi.org/10.1016/j.wasman.2022.11.024

[10] Di Natali, C., Buratti, G., Dellera, L., & Caldwell, D. (2024). Equivalent weight: Application of the assessment method on real task conducted by railway workers wearing a back support exoskeleton. Applied Ergonomics, 118, 104278. https://doi.org/10.1016/j.apergo.2024.104278

[11] Gaddis, E.S., Burch, V.R.F., Strawderman, L., Chander, H., Smith, B.K., Freeman, C., & Taylor, C. (2022). The impact of using wearable devices on the operator during manual material

handling tasks. International Journal of Industrial Ergonomics, 89, 103294. https://doi.org/10.1016/j.ergon.2022.103294

[12] Golabchi, A., Miller, L., Rouhani, H., & Tavakoli, M. (2022). Impact of passive back-support exoskeletons on manual material handling postures in construction. Proceedings of the International Symposium on Automation and Robotics in Construction, 2022-July, 359–366.

[13] Humadi, A., Nazarahari, M., Ahmad, R., & Rouhani, H. (2021). In-field instrumented ergonomic risk assessment: Inertial measurement units versus Kinect V2. International Journal of Industrial Ergonomics, 84, 103147. https://doi.org/10.1016/j.ergon.2021.103147

[14] Iyer, K. J., Narula, N., Binu, M., & Duffy, V. G. (2023). Improving facility layout using an ergonomics and simulation-based approach. Lecture Notes in Computer Science, 14028, 102-119. https://doi.org/10.1007/978-3-031-35741-1_9

[15] Johnen, L., Schaub, M., Mertens, A., Nitsch, V., & Brandl, C. (2022). Can cumulative loading estimates be used to assess the collective occupational risk of MSD? Evaluation of calculation methods for spinal cumulative loading. International Journal of Industrial Ergonomics, 92, 103361. https://doi.org/10.1016/j.ergon.2022.103361

[16] Kachlan, A., Lavender, S. A., & Sommerich, C. M. (2023). Effect of a simultaneous mental arithmetic task to a MMH lifting task on muscle activity in the trunk and shoulders. Proceedings of the Human Factors and Ergonomics Society, 67(1), 2160-2161. https://doi.org/10.1177/21695067231196250

[17] Kataria, K. K., Sharma, M., Kant, S., Suri, N. M., & Luthra, S. (2022). Analyzing musculoskeletal risk prevalence among workers in developing countries: an analysis of small-scale cast-iron foundries in India. Archives of Environmental and Occupational Health, 77(6), 486-503. https://doi.org/10.1080/19338244.2021.1936436

[18] Kim, H.K., Hussain, M., Park, J., Lee, J., & Lee, J.W. (2021). Analysis of active back-support exoskeleton during manual load-lifting tasks. Journal of Medical and Biological Engineering, 41(5), 704–714. https://doi.org/10.1007/s40846-021-00644-w

[19] Kjaer, C. R. H., Henriksen, C. B., Nwabuona, S. C., Petersen, M. N., & Ruepp, S. (2022). Classification of lifts using a smart insole. 2022 International Conference on Smart Applications, Communications and Networking (SmartNets 2022). https://doi.org/10.1109/SmartNets55823.2022.9994018

[20] Korkulu, S., & Bóna, K. (2022). Integration of ergonomic aspects into lot-sizing model of the production line supply process based on relaxation allowance and maximum endurance time. Periodica Polytechnica Transportation Engineering, 50(2), 205-215. https://doi.org/10.3311/PPtr.19947

[21] Liu, Y., Ojha, A., & Jebelli, H. (2024). Vision-based ergonomic risk assessment of back-support exoskeleton for construction workers in material handling tasks. Computing in Civil Engineering 2023: Resilience, Safety, and Sustainability - Selected Papers from the ASCE International Conference on Computing in Civil Engineering 2023, 331-339. https://doi.org/10.1061/9780784485248.040

[22] Madinei, S., Kim, S., Park, J.-H., Srinivasan, D., & Nussbaum, M.A. (2022). A novel approach to quantify the assistive torque profiles generated by passive back-support exoskeletons. Journal of Biomechanics, 145, 111363. https://doi.org/10.1016/j.jbiomech.2022.111363

[23] Madinei, S., Kim, S., Srinivasan, D., & Nussbaum, M.A. (2021). Effects of back-support exoskeleton use on trunk neuromuscular control during repetitive lifting: A dynamical systems analysis. Journal of Biomechanics, 123, 110501. https://doi.org/10.1016/j.jbiomech.2021.110501

[24] Muller, A., Mecheri, H., Corbeil, P., Plamondon, A., & Robert-Lachaine, X. (2022). Inertial motion capture-based estimation of L5/S1 moments during manual materials handling. Sensors, 22(17), 6454. https://doi.org/10.3390/s22176454

[25] Nurse, C.A., Elstub, L.J., Volgyesi, P., & Zelik, K.E. (2023). How accurately can wearable sensors assess low back disorder risks during material handling? Exploring the fundamental capabilities and limitations of different sensor signals. Sensors, 23(4), 2064. https://doi.org/10.3390/s23042064

[26] Park, J., Ye, Y., Du, J., & Srinivasan, D. (2024). Virtual reality simulation of exoskeleton-assistance for manual material handling. IEEE Access, 12, 105470-105480. https://doi.org/10.1109/ACCESS.2024.3434721

[27] Rajendran, M., Sajeev, A., Shanmugavel, R., & Rajpradeesh, T. (2021). Ergonomic evaluation of workers during manual material handling. Materials Today: Proceedings, 46, 7770-7776. https://doi.org/10.1016/j.matpr.2021.02.283

[28] Rocha, C., Dias, J., Moreira, A.P., Veiga, G., & Costa, P. (2022). A kinesthetic teaching approach for automating micropipetting repetitive tasks. International Journal of Advanced Manufacturing Technology, 118(1-2), 651-663. https://doi.org/10.1007/s00170-021-07925-3

[29] Schrøder Jakobsen, L., de Zee, M., Samani, A., Desbrosses, K., & Madeleine, P. (2023). Biomechanical changes, acceptance, and usability of a passive shoulder exoskeleton in manual material handling: A field study. Applied Ergonomics, 113, 104104. https://doi.org/10.1016/j.apergo.2023.104104

[30] Sharotry, A., Jimenez, J.A., Mediavilla, F.A.M., Wierschem, D., Koldenhoven, R.M., & Valles, D. (2022). Manufacturing operator ergonomics: A conceptual digital twin approach to detect biomechanical fatigue. IEEE Access, 10, 12774–12791. https://doi.org/10.1109/ACCESS.2022.3145984

[31] Shin, D. S., & Jeong, B. Y. (2022). Older female farmers and modeling of occupational hazards, wellbeing, and sleep-related problems on musculoskeletal pains. International Journal of Environmental Research and Public Health, 19(12), 7274. https://doi.org/10.3390/ijerph19127274

[32] Sultan, A. A. M., Gill, D. S., Azmi, M., Ching, N. T., Masuri, M. R. A., Othman, M. S., & Hayat Ahmad, S. N. M. (2022). Manual material handling assessments towards the working comfort in an automotive manufacturing company. Lecture Notes in Mechanical Engineering, 25, 338-346. https://doi.org/10.1007/978-981-16-8954-3_32

[33] Thylén, N., Wänström, C., & Hanson, R. (2023). Challenges in introducing automated guided vehicles in a production facility–interactions between human, technology, and

organisation. International Journal of Production Research, 61(22), 7809–7829. https://doi.org/10.1080/00207543.2023.2175310

[34] Valenzuela, E., Cano-Delgado, A., Cruz-Miranda, J., Rouret, M., Miccichè, G., Ros, E., Arranz, F., & Diaz, J. (2023). The IFMIF-DONES remote handling control system: Experimental setup for OPC UA integration. Fusion Engineering and Design, 192, 113776. https://doi.org/10.1016/j.fusengdes.2023.113776

[35] Wang, Z., Wang, W., Chen, J., Zhang, X., & Miao, Z. (2023). Posture risk assessment and workload estimation for material handling by computer vision. International Journal of Intelligent Systems, 2023, 2085251. https://doi.org/10.1155/2023/2085251

[36] Zhang, M., Grosse, E.H., & Glock, C.H. (2023). Ergonomic and economic evaluation of a collaborative hybrid order picking system. International Journal of Production Economics, 258, 108774. https://doi.org/10.1016/j.ijpe.2023.108774