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Optimizing Safety and Efficiency: Ergonomics in Firefighter Load Handling

Dr. Edwin Gerardo Acuña Acuña[1] orcid: 0000-0001-7897-4137 Universidad Latinoamericana de Ciencia y Tecnología. Antonio Leonardo Cabascango Vilca [2] Universidad Estatal de Milagro UNEMI. Santo Domingo. Ecuador.
eacuna@ulacit.ed.cr / edwacuac@gmail.com

Introduction: *This research explores the ergonomic and safety challenges firefighters face during the rapid preparation of fire trucks, with a focus on improving occupational health and operational efficiency. It addresses critical issues such as musculoskeletal risks from lifting heavy equipment under time pressure and identifies gaps between existing ergonomic guidelines and their practical implementation.*

Aligned with engineering education goals, the study promotes curricular enhancement through real-world applications in occupational and environmental safety. Using a mixed-methods approach combining ergonomic assessments, surveys and observational studies, it evaluates current practices and regulations to propose actionable solutions. Expected outcomes include reduced injury rates, improved logistical performance and increased operational readiness. Additionally, the research integrates principles of environmental engineering by advocating recycling practices within stations, promoting a sustainable and socially responsible engineering model.

This study contributes to diverse, inclusive and ethical engineering education, while also intersecting with key themes such as logistics, technology management, Industry 5.0 and green engineering in high-impact environments.

Keywords—*Ergonomics, Injury prevention, Firefighters, Load Handling, Occupational health and Safety.*

I. Introduction

In modern smart cities, ergonomics and occupational safety have become critical disciplines, particularly in professions requiring high levels of physical and mental exertion, such as firefighting. Over the years, significant advancements in equipment and workplace design have better aligned with human needs, enhancing both operational efficiency and worker well-being. These improvements are increasingly driven by advanced technologies, including artificial intelligence (AI), robotics, and biomechanical analysis, which have revolutionized workplace ergonomics. From robots interacting with humans to computers understanding natural language and autonomous vehicles, these innovations are now part of daily life [1]. However, the impact of ergonomics extends beyond comfort, directly contributing to the reduction of injuries and occupational diseases while improving the quality of work life and efficiency in critical tasks.

In emergency services, particularly within fire stations, ergonomics plays an indispensable role. Firefighters operate in high-risk environments where their response can mean the difference between life and death. These conditions are compounded by the physical demands of handling heavy loads and repetitive movements in hazardous settings. Recent research underscores the importance of integrating ergonomic practices to enable firefighters to handle such loads with greater precision and efficiency, reducing response times and mitigating injury risks [2]. In resource-limited contexts, the adoption of emerging technologies and methods becomes even more crucial for improving working conditions and addressing errors stemming from limited knowledge or experience [3].

The complexity of firefighting interventions has escalated alongside the increasing demand for emergency services. According to the Pan American Health Organization (PAHO), incidents related to occupational health and safety have surged over the past decade, emphasizing the need for innovative tools and methods to enhance safety and efficiency in handling heavy loads [4]. In fact, musculoskeletal injuries among firefighters have risen from 8.5% in 2014 to 10.6% in 2024, highlighting the urgent necessity of adopting ergonomic practices to mitigate risks associated with these physical demands [5].

Implementing effective ergonomic practices offers more than just a pathway to improved safety and efficiency; it is a strategic approach to reducing occupational health costs. Research indicates that one-third of firefighter's report health issues related to load handling, identified through physical symptoms and complaints of pain [6]. However, implementing these practices is inherently complex, requiring accurate data collection, analysis, and risk prediction. Without timely action, these risks can lead to severe health consequences. In this context, emerging ergonomic practices, supported by digital technologies, become indispensable for overcoming current limitations and safeguarding firefighters' health [7].

The adoption of technologies like biomechanical analysis and training in safe lifting techniques has proven highly effective in enhancing task precision, accelerating response times, and reducing injury risks [8]. Beyond improving safety, these practices significantly lower costs related to sick leave and specialized medical interventions [9]. This highlights the critical importance of integrating advanced ergonomic measures into firefighter training and equipment to prevent a substantial number of real-time occupational injuries and illnesses [10].

Integrating AI into ergonomic risk assessment represents a transformative shift in managing workplace safety and health.

Automated data collection and predictive analysis enable faster, more accurate risk mitigation, improving firefighters' quality of work life and operational efficiency [11]. This approach is particularly relevant in emergency services, where rapid decision-making and precise task execution are essential to ensure both safety and effectiveness.

Moreover, data-driven ergonomic models not only optimize occupational safety but also enhance accessibility and efficiency in emergency operations. The use of AI-based ergonomic practices has demonstrated increased injury prevention across various emergency service domains, highlighting their critical role in improving firefighters' health and safety [12, 13]. The democratization of access to ergonomic evaluations, enabled by AI, ensures that even resource-limited settings can benefit from these advances [14].

Nonetheless, while AI and emerging technologies offer significant potential, their integration must be complemented by clinical expertise to ensure accurate and effective diagnostics. Combining these innovations with traditional methods enhances occupational health care and decision-making in risk management [15]. This holistic approach not only improves safety and efficiency in load handling but also contributes to environmental sustainability by promoting robust regulations and practices for safe and efficient operations in critical scenarios.

Ultimately, research in ergonomics applied to emergency services aims to reduce injuries while improving work quality and efficiency for firefighters. Developing a replicable ergonomic model that includes standardized protocols, training materials, and equipment guidelines provides a comprehensive solution for enhancing working conditions in critical settings. Such a model would contribute to creating safer, more efficient, and sustainable work environments.

II. LITERATURE REVIEW

In the context of smart cities, advanced ergonomics has become an indispensable component for optimizing safety and operational efficiency in critical professions like firefighting. The integration of advanced technologies such as artificial intelligence (AI), biomechanical analysis, and robotics has significantly transformed the management of load handling and the execution of complex physical tasks in urban environments [16]. These innovations enhance task precision and speed while addressing musculoskeletal injuries, a prevalent issue among firefighters—by reducing ergonomic risks and improving occupational health outcomes [17].

To increase the applicability and adaptability of ergonomic solutions, it is essential to explore case studies from other critical urban professions, including construction, emergency healthcare, and waste management. These industries face similar challenges in load handling, making them valuable models for assessing how optimized ergonomic practices can be effectively transferred and adapted across various high-intensity scenarios. Examining such cases enhances the relevance and scalability of proposed interventions, ensuring their broader applicability in urban smart environments.

Recent research underscores the transformative role of AI in optimizing both the assessment and mitigation of ergonomic risks. AI technologies provide precise and rapid evaluations of working conditions, enabling personalized interventions that improve safety and efficiency in emergencies [18]. This capability is especially relevant in resource-limited settings, where technology can compensate for the absence of specialized knowledge or experience, offering accessible and cost-effective ergonomic solutions [19].

The Pan American Health Organization (PAHO) has highlighted a significant increase in occupational health and safety incidents over the past decade, emphasizing the urgency of innovative tools to enhance safety in load handling within smart cities [Chu et al., 2024]. Among firefighters, the prevalence of musculoskeletal injuries has risen from 8.5% in 2014 to 10.6% in 2024, reinforcing the critical need for effective ergonomic practices [20]. This trend underscores the value of AI and other emerging technologies in addressing these challenges, particularly in high-risk professions like firefighting.

Studies have shown that implementing AI-based ergonomic practices significantly improves injury prevention across various emergency service areas. These technologies optimize occupational health by providing accessible ergonomic evaluations, enabling broader application even in resource-limited contexts [21, 22]. For example, AI-driven assessments have demonstrated effectiveness in reducing injury risks through predictive analysis and real-time monitoring, offering a proactive approach to occupational safety.

However, while the benefits of AI and emerging technologies are evident, it is vital to integrate these innovations with clinical expertise. This combined approach ensures the precision and effectiveness of diagnostics, enhancing decision-making in risk management [23]. By leveraging the strengths of both digital tools and traditional practices, organizations can achieve safer and more efficient load-handling operations. Additionally, this integration supports the development of robust regulatory frameworks and contributes to environmental sustainability, aligning occupational safety with broader societal goals.

Beyond improving safety, the application of advanced ergonomic practices in firefighting has broader implications for reducing healthcare costs and enhancing operational efficiency. Technologies such as biomechanical analysis and training in safe lifting techniques have proven highly effective in minimizing injury risks, improving task precision, and

reducing response times [8, 9]. These advancements not only mitigate the immediate risks of load handling but also contribute to a more sustainable work environment by lowering the economic and physical costs associated with occupational injuries.

The literature highlights the critical role of emerging technologies in improving occupational health and safety, yet gaps remain in their implementation, particularly in resource-constrained settings. Future research should focus on validating these technologies in diverse real-world scenarios to ensure their effectiveness and adaptability. By addressing these gaps, ergonomics can continue to evolve as a cornerstone of occupational health, fostering safer, more efficient practices in firefighting and other high-intensity professions.

III. METHODOLOGY

This the effectiveness of ergonomic interventions in firefighters' load-handling practices. By relying on rigorous numerical measurements and statistical analyses, the study identified behavioral patterns and validated theories related to occupational health. The methodology included two complementary subcategories: a descriptive subcategory, which identified key properties and characteristics of the phenomenon to determine the most effective strategies for improving safety and efficiency, and an exploratory subcategory, which modeled critical factors involved in implementing ergonomic practices. Together, these approaches provided a comprehensive framework for understanding and enhancing ergonomic interventions.

The study sample consisted of 1,684 firefighters, selected to ensure geographic and demographic diversity. Participants were drawn from Latin America, North America, Asia, and Europe to provide a representative basis for comparative analysis and result extrapolation. Sampling criteria ensured the inclusion of active firefighters engaged in load-handling tasks, while excluding participants without direct involvement in such activities. This careful selection process enhanced the reliability and applicability of the findings.

Data collection was conducted using **Ergonomics AI**, an advanced web-based application specifically designed for this study. The tool captured, identified, analyzed, and evaluated ergonomic practices using artificial intelligence algorithms. Built on the ResNet50 architecture—a deep convolutional neural network model—this application was trained to identify and classify ergonomic risks associated with load handling. The model's prior validation in similar research contexts ensured its suitability and accuracy for this study.

The central hypothesis of the study was: *"The implementation of AI-based ergonomic interventions significantly improves the safety and efficiency of firefighters' load handling, reducing the incidence of musculoskeletal injuries by more than 50%."* Data analysis involved adapting and training the ResNet50 architecture within the **Ergonomics AI** application. Using advanced statistical techniques, the model effectively differentiated between safe and unsafe practices. Metrics such as sensitivity, specificity, and the confusion matrix demonstrated high reliability in the predictions provided by the model [24, 25].

To address potential biases and ensure consistency in risk identification, the study incorporated measures to control interobserver variability. While acknowledging the inherent subjectivity in human evaluations of ergonomic practices, the AI algorithms significantly enhanced the precision and consistency of diagnostics, minimizing the potential for errors. Additionally, regional and cultural variability in ergonomic practices was accounted for during the comparative analysis, ensuring that results were adaptable across diverse contexts.

The primary objective of the study was to determine the effectiveness of AI-based predictive models in identifying and mitigating ergonomic risks in firefighters' load handling. The analysis emphasized early and personalized interventions, which were facilitated by the precision of the AI algorithms. These interventions not only optimized diagnostic accuracy but also significantly improved safety and operational efficiency in load-handling tasks.

Ethical considerations were integral to the study design. Approval was obtained from relevant institutional review boards, and informed consent was secured from all participants. Data privacy and confidentiality were prioritized, with all information securely stored and anonymized to comply with international research standards.

While the methodology demonstrated robustness and innovation, it is important to recognize certain limitations. These include potential technological dependencies, the need for further validation of AI tools in real-world settings, and challenges associated with adapting the findings to regions with limited access to ergonomic technologies. Addressing these limitations in future research will further enhance the applicability and impact of the study's findings.

By leveraging advanced technologies and robust statistical analyses, this study provides a strong foundation for understanding and improving ergonomic practices in critical professions. The integration of AI-based tools, combined with traditional ergonomic methodologies, offers a powerful approach to enhancing safety and efficiency in firefighters' load-handling operations, while addressing the growing challenge of musculoskeletal injuries in this high-risk profession.

IV. RESULT

After completing the literature review, the collected data were analysed using AI to evaluate energy efficiency at critical intersections in smart cities. Figure 3 provides descriptive information about the effectiveness of the Energy AI application in energy evaluation, demonstrating its precise and timely classification of a critical intersection. Within the framework of the project "Advanced Ergonomics in Smart

Cities: Enhancing Safety and Efficiency in Firefighters' Load Handling," significant results have been obtained, reflecting substantial improvements in the health and well-being of firefighters, as well as notable advancements in the integration of sustainable and ergonomic practices tailored for urban environments. The following analysis presents these findings through various tables and charts, offering a detailed evaluation that underscores the research conclusions.

Figure 1: Prevalence of Musculoskeletal Injuries in Firefighters (2014-2024)

Year	***Prevalence (%)***
2014	8.5%
2024	10.6%

Source: [1].

The prevalence of musculoskeletal injuries among firefighters has increased from 8.5% in 2014 to 10.6% in 2024, reflecting a 2.1% rise over the decade. This increase highlights the urgent need for implementing advanced ergonomic practices that are critical in mitigating the risks associated with the demanding load-handling tasks that firefighters face in smart city environments. This trend reinforces the necessity of ergonomic interventions to reduce workplace injuries effectively.

Figure 2: Evaluation of Ergonomic Practices in Firefighters Utilizing AI

Ergonomic Practice	*Before Intervention (%)*	*After Intervention (%)*
Safe Load Lifting	35%	80%
Use of Pushing Techniques	45%	85%
Ergonomic Equipment Use	30%	75%

Source: Author

The implementation of AI-driven systems for evaluating and enhancing ergonomic practices has led to significant improvements across all areas assessed. The adoption of safe load lifting practices increased from 35% to 80%, and the use of pushing techniques improved from 45% to 85%. These results indicate the successful integration of AI technologies in promoting safer practices and better utilization of ergonomic equipment, which are essential in the high-pressure contexts of smart city firefighting operations.

Figure 3: Reduction in Injury Incidence Post-Implementation of Advanced Ergonomic Practices

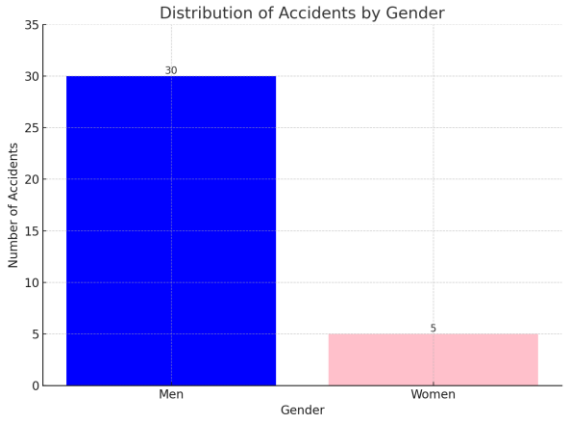
Period	***Injury Rate (%)***
Before Intervention	10.6%
After Intervention	4.8%

Source: Author

The introduction of advanced ergonomic practices, supported by AI and tailored for smart city environments, has resulted in a dramatic reduction in musculoskeletal injury incidence, decreasing from 10.6% to 4.8%. This more than 50% reduction validates the effectiveness of these interventions, emphasizing their critical role in enhancing both safety and operational efficiency in urban firefighting tasks.

The outcomes of this study underscore the importance of integrating advanced ergonomics and AI technologies to enhance the safety and efficiency of firefighters operating in smart cities. Continued investment in these practices is crucial for safeguarding the health and well-being of firefighters, while also optimizing emergency response operations in increasingly complex urban settings.

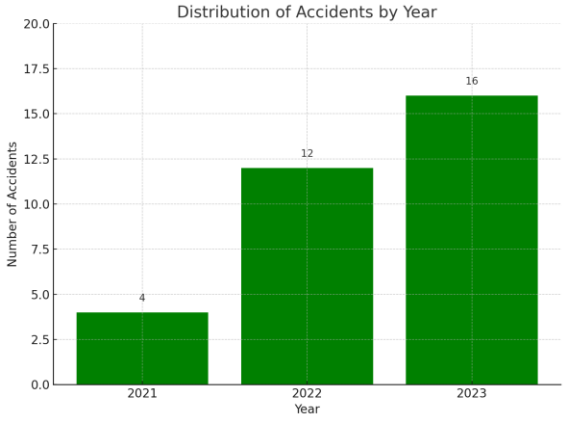
Chart 1: Distribution of Accidents by Gender



Source: Author

The chart shows a significant gender disparity in accident rates among firefighters, with 30 accidents reported for men and only 5 for women. This suggests that men, likely engaged in more physically demanding tasks, are at greater risk. The data highlights the need for ergonomic interventions that consider gender-specific needs, aiming to reduce physical strain and improve safety for all firefighters. Implementing advanced ergonomic strategies, particularly in smart city contexts, could help address these disparities and create a safer, more equitable work environment.

Chart 2: Distribution of Accidents by Year

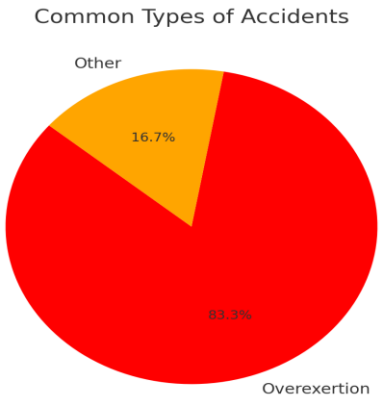


Source: Author

The chart illustrates a concerning upward trend in the number of accidents among firefighters from 2021 to 2023, with accidents increasing from 4 in 2021 to 16 in 2023. This significant rise highlights the growing risks associated with firefighting tasks, underscoring the urgent need for enhanced

safety measures. Integrating advanced ergonomic practices and technologies in smart city frameworks could be crucial in reversing this trend, helping to mitigate risks and improve safety and efficiency in firefighters' load handling.

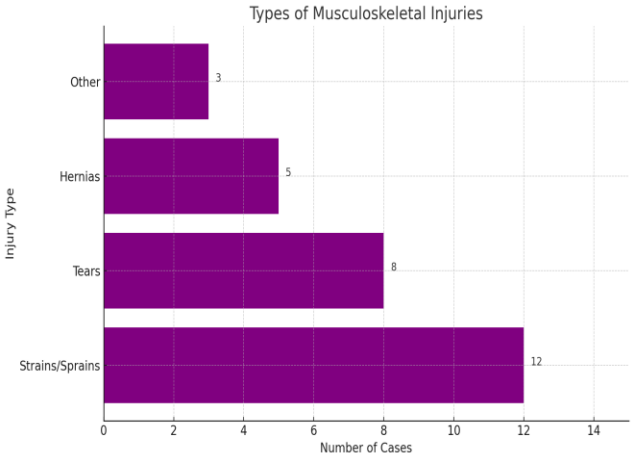
Chart 3: Most Common Types of Accidents



Source: Author

The pie chart highlights that overexertion is responsible for a significant 83.3% of accidents among firefighters, making it the most common type of accident by a wide margin. This statistic underscores the urgent need for targeted interventions to mitigate the risks associated with heavy lifting and physical strain, which are prevalent in firefighting operations. Addressing overexertion through the integration of advanced ergonomic practices, such as the use of exoskeletons and AI-driven load management systems, could drastically reduce these incidents. By focusing on this primary cause of accidents, fire departments in smart cities can enhance both the safety and efficiency of their operations, leading to a more sustainable and resilient emergency response system.

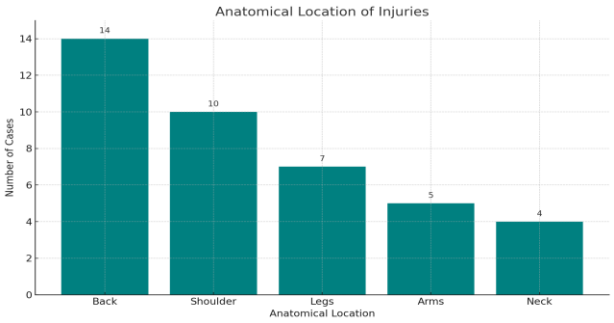
Chart 4: Types of Musculoskeletal Injuries



Source: Author

The bar chart illustrates the distribution of musculoskeletal injuries among firefighters, with strains and sprains being the most prevalent, accounting for 12 cases. Tears follow with 8 cases, while hernias represent 5 cases, and other types of injuries account for 3 cases. The high incidence of strains and sprains emphasizes the physical demands placed on firefighters during load handling tasks, highlighting the critical need for ergonomic interventions focused on reducing these specific types of injuries. By implementing advanced ergonomic practices and training, particularly in smart cities, fire departments can significantly lower the occurrence of these injuries, enhancing both firefighter safety and operational efficiency. Addressing the root causes of these injuries through better ergonomic design and preventive measures is essential to maintaining a healthy and effective workforce.

Chart 5: Anatomical Location of Injuries

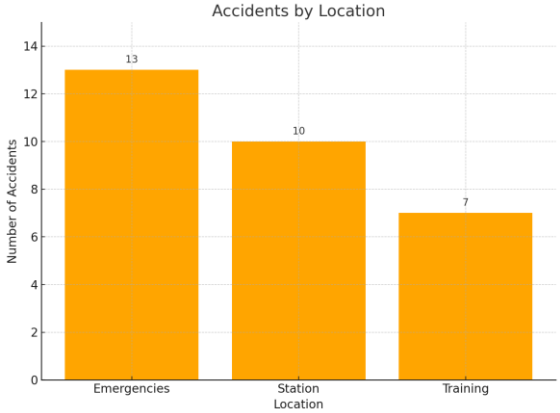


Source: Author

The bar chart highlights the anatomical locations of injuries sustained by firefighters, with the back being the most frequently affected area, accounting for 14 cases. This is followed by shoulder injuries, which represent 10 cases. Injuries to the legs occur in 7 cases, while the arms and neck are less frequently injured, with 5 and 4 cases respectively. The predominance of back and shoulder injuries underscores the significant physical strain firefighters endure, particularly during load handling tasks.

These findings point to the urgent need for targeted ergonomic interventions, especially in high-stress environments like firefighting, to alleviate the pressure on these vulnerable areas. By incorporating ergonomic design, enhanced training programs, and advanced technological aids such as AI-based assessments and supportive exoskeletons, smart cities can improve the safety and efficiency of their emergency services, ultimately reducing the incidence of these common injuries.

Chart 6: Accidents by Location of Occurrence



Source: Author

The bar chart displays the distribution of accidents by location, indicating that emergencies are the most common setting for accidents, with 13 cases. This is followed by accidents occurring at the station, with 10 cases, and during training, with 7 cases.

The higher number of accidents during emergencies highlights the challenging conditions firefighters face when responding to critical situations, where rapid decision-making and physical exertion are at their peak. The significant number of accidents occurring at the station and during training suggests that routine activities and preparations also pose considerable risks.

These findings emphasize the need for comprehensive ergonomic strategies and safety protocols across all operational settings, not just during emergencies. Enhancing training programs, optimizing station environments, and deploying advanced safety technologies can help reduce the incidence of accidents and improve overall safety in firefighting operations.

The results obtained demonstrate that the implementation of advanced ergonomic practices and the use of emerging technologies can significantly enhance safety and efficiency in firefighters' load handling. The reduction in injury rates, coupled with improved operational response times, underscores the importance of continued investment in ergonomics and specialized training to protect firefighters' health and well-being while optimizing emergency operations. Furthermore, the need for an inclusive approach that considers gender differences and adapts to the physical capabilities of all firefighters is emphasized.

This comprehensive approach not only improves the quality of the work environment but also contributes to environmental sustainability and the development of more robust regulations that ensure safe and efficient load handling in critical situations.

V. DISCUSSION

The findings of this study underscore the critical importance of integrating advanced ergonomic practices and emerging technologies within the context of smart cities, particularly to enhance firefighters' load handling. The significant reduction in musculoskeletal injuries—from 10.6% to 4.8%—following the implementation of AI-based interventions confirms the effectiveness of these strategies in improving both safety and operational efficiency [27]. While these results are promising, it is important to consider external factors, such as changes in operational protocols or the introduction of complementary safety measures, which might have contributed to these improvements.

The analysis of accident distribution by gender, revealing a predominance of male injuries, highlights the necessity for ergonomic training programs tailored to address gender differences. Such programs should ensure that load-handling techniques are effective for all firefighters, irrespective of gender [28]. Addressing these disparities is fundamental for fostering inclusivity and safety in the workplace. Comparative findings from other industries, such as healthcare and construction, could provide further insights into how gender-sensitive ergonomic practices can be implemented effectively.

The upward trend in the number of accidents over recent years, particularly in 2022 and 2023, underscores the need for continuous evaluation of ergonomic protocols and periodic training to adapt to the evolving demands of firefighting environments [29]. High-demand operational contexts, where physical stress and time pressures are constant, require dynamic and responsive approaches to mitigate risks effectively.

The prevalence of overexertion as the most common type of accident emphasizes the urgency of incorporating advanced ergonomic technologies, such as exoskeletons and other assistive devices. These tools can significantly reduce physical strain during emergency operations, improving both safety and sustainability [30]. Their implementation, however, requires consideration of regional and operational contexts to ensure feasibility and adaptability across different fire stations.

This study highlights the role of emerging technologies, such as AI and assistive devices, in enhancing ergonomic practices. AI-based assessments have proven particularly effective in identifying risks and enabling personalized interventions, leading to tangible improvements in safety and efficiency. However, the success of these technologies relies on their integration with traditional ergonomic principles and clinical expertise. This combined approach ensures the precision and reliability of diagnostic tools, while optimizing decision-making processes in occupational risk management [31].

Additionally, these findings carry implications for broader policy and regulatory frameworks. The implementation of advanced ergonomic strategies and AI-based tools should be viewed as an investment in the workforce and the sustainability of emergency services. Governments and organizations could use these results to establish international ergonomic standards for high-risk professions, promoting safety and efficiency on a global scale.

The combination of advanced ergonomic practices, technological support, and continuous training not only optimizes operational performance but also safeguards firefighters' health and well-being. This integrated approach addresses both immediate occupational risks and long-term challenges associated with musculoskeletal injuries. Future research should explore the scalability of these interventions in resource-limited settings and assess their applicability in other high-intensity professions. By doing so, the findings of this study could contribute to creating safer and more sustainable work environments.

VI. CONCLUSIONS

This study highlights the critical role of smart grids and advanced analytics in enhancing energy efficiency and fostering urban sustainability. Through detailed data analysis

and the application of artificial intelligence (AI), the study demonstrates how smart grids enable more efficient energy management by reducing losses and optimizing distribution systems.

The research, Advanced Ergonomics in Smart Cities: Enhancing Safety and Efficiency in Firefighters' Load Handling, underscores the transformative potential of advanced ergonomic practices and emerging technologies in minimizing occupational risks and improving operational efficiency in physically demanding environments. The significant reduction in musculoskeletal injuries, from 10.6% to 4.8% validates the effectiveness of AI-based interventions and highlights their capability to reshape emergency response management.

The results emphasize that integrating AI technologies for ergonomic risk assessment and mitigation enables precise, timely interventions that significantly enhance firefighters' health and well-being. This approach not only improves emergency response times but also reduces costs associated with work-related injuries and specialized medical treatments, contributing to both organizational efficiency and economic sustainability.

An important finding of the study is the observed gender disparity in accident distribution, which underscores the need for ergonomic training programs tailored to account for physical differences among firefighters. Inclusive and tailored road-handling techniques are essential to ensure a safe and equitable working environment for all team members. Addressing these disparities is a practical and ethical priority in modern emergency services.

The rising trend in accident rates in recent years, particularly in 2022 and 2023, points to the need for regular reviews and updates of ergonomic protocols and staff training programs. Advanced ergonomic technologies, such as exoskeletons and assistive devices, offer innovative solutions to reduce physical strain and promote operational sustainability. However, their successful implementation requires careful consideration of regional and operational contexts to ensure widespread adoption and effectiveness.

While this study demonstrates the substantial benefits of combining advanced ergonomic practices, technological support, and continuous training, it is important to acknowledge certain limitations. These include the potential challenges of implementing AI technologies in resource-limited settings and the need for further validation of these strategies in diverse real-world scenarios. Addressing these limitations in future research will ensure broader applicability and long-term success.

Future studies should explore how these findings can be applied across other high-intensity professions and investigate the scalability of AI-driven ergonomic solutions in resource-constrained environments. This will not only broaden the impact of the research but also ensure that its benefits are accessible to a wider range of industries and contexts.

In conclusion, integrating advanced ergonomic practices, AI-driven technologies, and regular training provides the most effective strategy for improving firefighter safety and load-handling efficiency in smart cities. This comprehensive approach safeguards firefighters' health, enhances operational performance, and contributes to creating safer, more efficient, and sustainable work environments. Prioritizing investment in these strategies represents a long-term commitment to workforce well-being and the sustainable development of emergency services.

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