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Abstract

Physical ergonomics is critical in safeguarding worker safety and well-being, particularly in demanding work environments such as maintenance tasks involving complex engineering systems (CES). The ergonomics field is evolving with new technological tools, offering innovative approaches to enhance current assessment protocols. This study proposes a conceptual framework integrating advanced technological tools, specifically, Three-Dimensional Computer-Aided Design (3D-CAD) and Virtual Reality (VR), with conventional mixed methods approaches to optimize ergonomic solutions for railway maintenance workers. The proposed framework combines quantitative data, such as anthropometric measurements and workstation evaluations, with qualitative insights from worker feedback, ensuring a holistic approach to ergonomic assessment. By incorporating VR technology, the framework creates an immersive environment where workers can interact with full-scale models of their workstations, providing detailed feedback essential for both proactive and corrective ergonomic interventions. The study demonstrates that this integrated approach effectively addresses ergonomic challenges by merging the objectivity of quantitative analysis with the contextual depth of qualitative insights. The findings suggest that the proposed framework enhances worker performance and safety and supports continuous improvement in ergonomic practices. The study concludes that this framework is valuable for comprehensive research into ergonomic challenges in railway maintenance and offers a versatile methodology for improving worker well-being in similar high-risk industries.

Keywords : Ergonomics; Railway; Maintenance; 3D-CAD; VR; Mixed methods

INTRODUCTION

Overview

As a scientific discipline, ergonomics evaluates human and system interaction to enhance safety, well-being, and performance in various work environments (Tosi, 2023). This field is particularly crucial in physically demanding or complex work settings, where practical ergonomic assessment can significantly reduce risks and improve overall efficiency. The engineering field has recently seen a renewed emphasis on ergonomics, especially in the context of Complex Engineering Systems (CES). Integrating ergonomic principles in the design and development of CES is now recognized as essential for ensuring safety and operational feasibility. However, traditional approaches often prioritize design and development considerations over operational ergonomics, potentially compromising the long-term viability of these systems. Furthermore, conventional assessment methods lack the dynamic and interactive analysis of systems, which is necessary for the effective identification and active intervention of ergonomic challenges in the workplace (Tosi, 2023). This has, therefore, created a need to re-examine the current ergonomic approaches and create a system that adapts to emerging challenges and integrates current and emergent technology.

Railway maintenance is an ideal manifestation of CES, involving complex interconnected systems and workstations that must work in tandem to guarantee operational feasibility. This thus places railway maintenance workers at the center of ergonomic challenges, as these workers are often exposed to complex routine tasks requiring technical skill and manual input. Consequently, these workers are exposed to pertinent risks, including decreased performance, cognitive fatigue, and an increased risk of Musculoskeletal Disorders (MSDs) (Mujmule et al., 2020).

The congruence of all these factors highlights the need for a conceptual framework that integrates current ergonomic assessment methodologies with practical technological tools, including Three-dimensional Computer-Aided Design (3D-CAD) and Virtual Reality (VR). Therefore, this study examines how existing and emerging technology, particularly 3D-CAD and VR, can be integrated into mixed-method approaches involving qualitative and quantitative designs to optimize ergonomic assessments. Railway maintenance workers are considered ideal for the study due to their regular exposure to CES, which encompasses complex and physically demanding tasks.

Background of Study

As ergonomics continues to evolve, it is increasingly recognized as a means to enhance worker safety and performance and as a critical component of Continuous Quality Improvement (CQI) and overall operational efficacy. This broadened perspective highlights the importance of systematically evaluating the interactions between workers and systems, underscoring the need for ongoing ergonomic monitoring and refinement to maintain high standards and reduce outcome variability. Railway maintenance exemplifies the importance of this approach, especially as the sector undergoes a transformative shift, replacing outdated systems with modern technologies. Despite these technological advancements, studies show that many maintenance tasks still suffer from suboptimal work design (Abdussalam & Ardiyanto, 2024). These deficiencies can be addressed by adopting modern ergonomic principles that leverage emerging technologies to establish a framework for continuous monitoring and improvement of worker safety and performance.

Integrating modern technology into railway operations has significantly impacted safety and quality standards, with a strong focus on automation and advanced monitoring systems. Digital twin models have revolutionized railway maintenance by offering virtual representations of physical assets, enhancing simulation capabilities, and improving decision-making processes (Dimitrova & Tomov, 2021). Additionally, the implementation of condition-based monitoring and predictive maintenance, leveraging wireless sensor networks and AI algorithms, has enhanced the proactive maintenance of railway infrastructure by addressing issues before failures occur (Z. A. Alrahman & Adham, 2024). While these innovations enable real-time monitoring and problem-solving, they often overlook how workers interact with physical systems and workstations.

Three-dimensional computer-aided design (3D-CAD) has become increasingly integrated with ergonomic assessment tools to enhance workplace design and maintenance activities across various industries, including railway operations. Systematic ergonomic approaches now utilize 3D-CAD software, such as CATIA, to optimize maintenance workstations by suggesting ideal modifications based on worker anthropometric data (Mujmule et al., 2020). Furthermore, the combination of Virtual Reality (VR) with 3D-CAD is emerging as a vital tool in ergonomic analysis, mainly through Digital Human Model Simulations (Kumar & Ashok, 2021).

The evolving nature of railway operations necessitates incorporating contemporary technologies not only in customer-centric areas but also in the back-end processes, particularly in maintenance activities. A key challenge, however, is the seamless integration of these technologies by maintenance personnel. Despite technological advancements, safety-related incidents persist, often due to poor human-machine interactions and human error (Hamid et al., 2021). Integrating 3D-CAD and VR with ergonomic assessment methodologies offers a promising solution to bridge the existing human-machine gaps. This study posits that such a framework can be developed by combining physical ergonomic factors with workers' behavioural attitudes toward tasks. By focusing on specific challenges faced at workstations, the most critical issues pertinent to worker safety and performance can be realized. Advanced technical tools, including 3D-CAD and VR, can then be leveraged to assess these issues and provide interceptive measures that address emergent ergonomic risks.

Ergonomics Assessments in High-Risk Work Environment

Ergonomics is a well-established field in industrial sectors, where physically demanding tasks pose significant risks to worker safety and well-being (Chen & Wu, 2023). In high-risk environments such as railway maintenance, workers are frequently exposed to awkward posture, repetitive motions, and physically strenuous activities. Traditional ergonomic assessments, which primarily focus on static postural analysis, often fall short of capturing the dynamic nature of these tasks (Tosi, 2023). This limitation has contributed to the rise of Musculoskeletal Disorders (MSDs), underscoring the need for more advanced ergonomic solutions tailored to the unique challenges of high-risk work environments (Abdussalam & Ardiyanto, 2024).

Human Factors and Ergonomics (HFE) are essential for optimizing the interaction between Complex Engineering Systems (CES), work environments, and human well-being. These multidimensional interactions require a deep understanding of the technical aspects of CES and the human elements and interfaces within work systems (Reiman et al., 2021). The International Ergonomics Association (IEA) defines ergonomics, often used interchangeably with human factors, as "the scientific discipline that applies theoretical principles, data, and methods to understand interactions among humans and other elements of a system, aiming to optimize both human well-being and overall system performance" (IEA, 2024). Therefore, ergonomics' primary goal is to enhance human well-being and maximize system efficiency in high-risk work environments.

Modern ergonomic approaches often incorporate multiple overlapping disciplines. For example, this study focuses on ergonomics in design, technology, environment, practice, and education. To consolidate these diverse aspects, the IEA has identified three core domains of ergonomics: physical ergonomics, cognitive ergonomics, and organizational ergonomics. As shown in Figure 1, this study emphasizes the domain of physical ergonomics, which addresses the physical interactions between workers and their environments.

Tosi (2023) emphasizes that ergonomics is a methodological approach and an intervention philosophy involving various areas and skills that unite to achieve common goals for improving safety, performance, and system functionality. Ergonomics is applicable across a wide range of sectors, including design, sustainability, workplace safety, and human-computer interaction (Tosi, 2023). These applications can be refined into critical disciplines, such as philosophy (addressing social needs), theory, practice and education, management, design, and technology and environment (Bisbey et al., 2021).

Within high-risk environments like railway maintenance, advancing ergonomic assessments has become critical and necessary to the sustainability of routine operations (Abdussalam & Ardiyanto, 2024). This can be achieved by adopting comprehensive methodologies that examine workers' physical demands and attributes and their interactions with complex systems. Optimized ergonomic solutions that mitigate risks and contribute to improving worker safety and performance are, therefore, idealized.

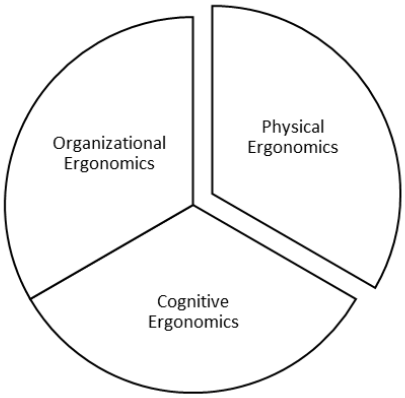

Figure 1. Human Factors Ergonomics Domains (IEA, 2024)

Ergonomics Assessment Methodology

Among the three domains of HFE, physical ergonomics explicitly addresses issues associated with the occupational environment pertinent to workers' physiological and psychological needs (Malaysia D. O. S. H., 2017). This study centers on this domain as the foundation for developing a framework to optimize ergonomic assessments in railway maintenance. The Malaysian Department of Occupational Safety and Health (DOSH) provides guidelines that can be applied within this context to establish a robust conceptual framework tailored for railway maintenance workers.

Two fundamental approaches, proactive and reactive, are typically employed to initiate an ergonomic risk assessment (ERA) within the physical domain. The proactive approach identifies and mitigates ergonomic risk factors before they manifest as injuries, diminished performance, or the development of musculoskeletal disorders (MSDs). Proactive measures are preventive, aiming to create safer work environments by anticipating and eliminating potential ergonomic hazards.

The reactive approach, in contrast, is applied to address ergonomic risks and challenges as they arise, typically in response to incidents, injuries, or observed declines in worker performance. This approach is more adaptive, allowing organizations to respond to changes in the work environment and tasks as they evolve.

Organizations like those involved in railway maintenance, which face ongoing operations and frequent procedural changes, often need to balance both proactive and reactive approaches. The dynamic nature of their work environments necessitates a flexible ergonomics strategy that can pre-emptively address risks while being responsive to emerging challenges.

The Malaysian DOSH advocates an ERA assessment methodology encompassing proactive and reactive approaches, as illustrated in Figure 2. As shown in the figure, A, B, and C represent proactive measures, emphasizing hazard identification before an initial ERA is conducted. D and E represent reactive approaches, focusing on evaluating and remedying ergonomic challenges after an initial ERA has been undertaken and these challenges identified. This study adopts a hybrid approach, combining elements of both proactive and reactive methodologies. Doing so creates a comprehensive and adaptive ergonomic assessment framework that can effectively manage the unique challenges faced in railway maintenance.

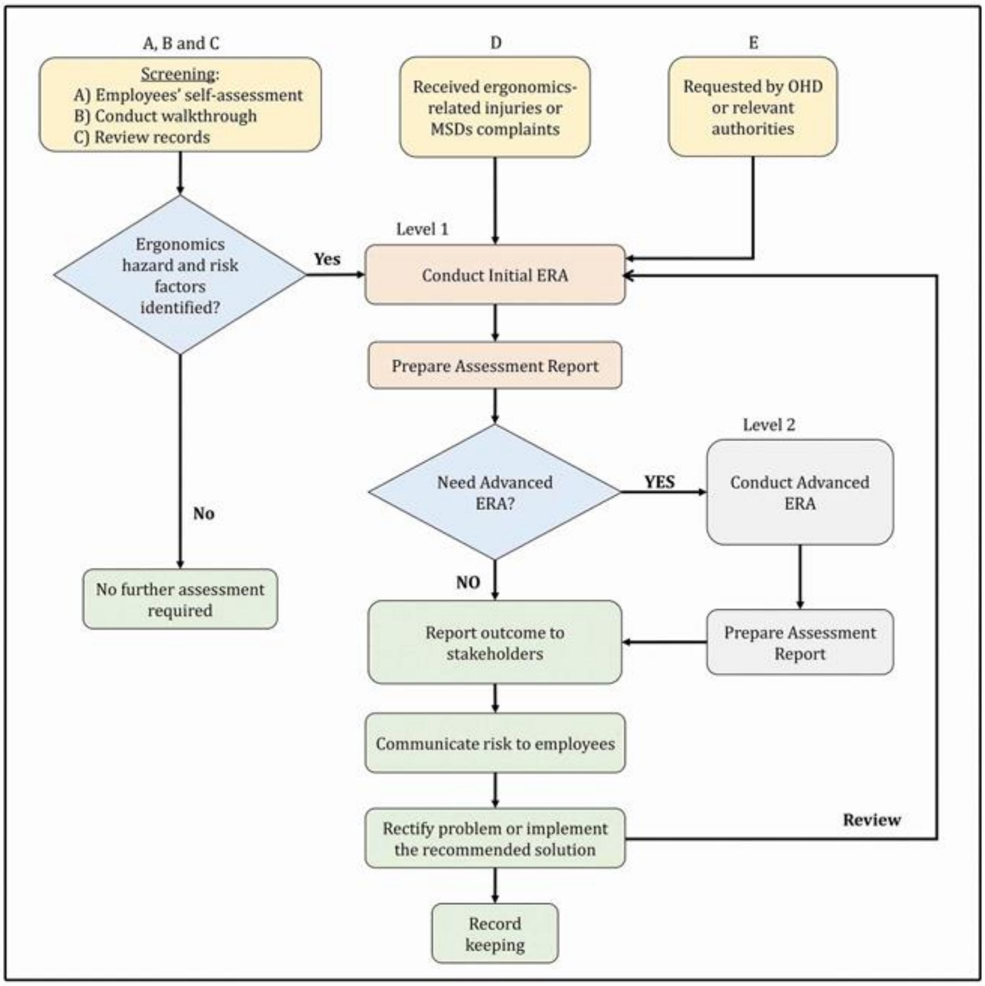

Figure 2. Physical Ergonomic Risk Assessment (Malaysia D. O. S. H., 2017)

Technological Advancements in Ergonomics Assessment

Recent advancements in ergonomic assessments have introduced technologies like 3D-CAD and Virtual Reality (VR), offering a more dynamic and immersive analysis of worker-environment interactions (Lukačević et al., 2020). 3D-CAD is particularly useful for creating detailed models of workstations, allowing for precise simulations of worker movements. Conversely, VR offers an interactive, real-time environment where workers can engage with full-scale models. Despite their potential, these technologies have limited application in high-risk environments like railway maintenance, where real-time ergonomic feedback is critical (Rossoni et al., 2019).

3D-Computer Aided Dimensions (3D-CAD)

A vital methodology for visually presenting these designs is three-dimensional Computer-Aided Design (3D-CAD). 3D-CAD utilizes specialized software to create detailed, three-dimensional models of physical components, offering a dynamic and accurate representation of the design before it is physically realized (Kolbasin & Husu, 2018).

Since the 1980s, 3D-CAD has advanced significantly, evolving from a simple drafting tool to an integral part of the entire product development cycle. This includes integration with Computer Aided Engineering (CAE) for analysis and simulation, and Computer-Aided Manufacturing (CAM) for planning and controlling the manufacturing process (Kolbasin & Husu, 2018). The coalescence of these processes facilitates the seamless transition from conceptual design to production, ensuring that ergonomic considerations are incorporated at every stage.

In the context of ergonomic assessment, 3D-CAD is indispensable for designing tools, equipment, and workstations that are tailored to address workers' needs. It allows designers and engineers to simulate and analyse human interaction with the environment, ensuring that the final design minimizes physical strain and maximizes comfort and efficiency (R. A. Alrahman et al., 2022). Among the various 3D-CAD software available, the Computer-Aided Three-Dimensional Interactive Application (CATIA), developed by Dassault Systèmes, stands out for its comprehensive features and user-friendly interface (Systèmes, 2023).

CATIA offers tools geared explicitly towards ergonomic risk assessment (ERA). One of the most notable tools within CATIA is the Rapid Upper Limb Assessment (RULA) module, designed to evaluate the ergonomic risks associated with upper body postures during various tasks. RULA analyses factors such as arm, wrist, and neck positions to identify areas most prone to injury or discomfort (Mahantesh et al., 2023). This is evidenced by studies such as those conducted by Yang et al. (2023) that applied digital modelling to conduct an ergonomic assessment of overhead maintenance of vehicle-mounted radar antennae. In the study, the RULA tool determined areas of the body most susceptible to ergonomic risks (Yang et al., 2023). Similarly, RULA has also been effectively used to conduct ERA for working postures among maintenance workers, highlighting its role in identifying high-risk positions that could lead to musculoskeletal disorders (MSDs) (Yek et al., 2023).

CAD-VR Integration

Integrating traditional 3D-CAD methods with Virtual Reality (VR) technology has been a significant focus of recent research to enhance the efficiency and effectiveness of design and testing procedures. Rossoni et al. (2019) note that substantial progress has been made in the last few years toward incorporating CAD models within Product Lifecycle Management (PLM) tools, which are crucial for managing the entire lifecycle of a product from inception through design, manufacturing, and disposal.

According to the study, two fundamental methods exist for integrating CAD and VR. The first method uses a toolkit where models are initially created in a traditional CAD environment. These CAD files are then automatically converted in real time for visualization and assessment within the VR environment. This approach allows designers to take advantage of the robust modelling capabilities of CAD while benefiting from VR's immersive and interactive features. The second method entails developing models directly within the VR environment, utilizing a library of existing repositories (Rossoni et al., 2019). The schematic in Figure 3 illustrates these methods.

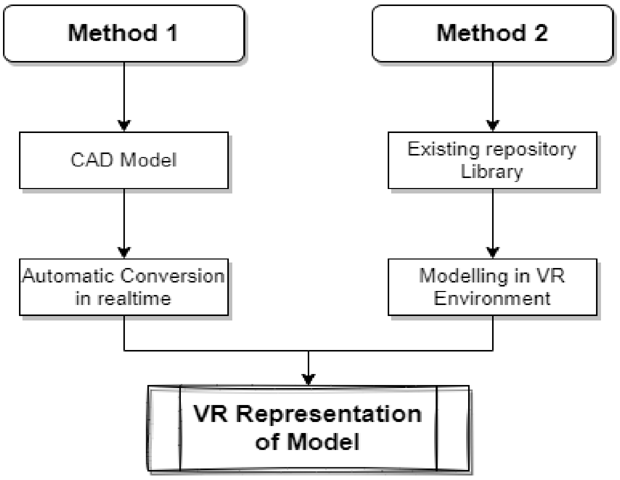

Figure 3. Common Methods of CAD-VR Integration

The most widely applied technique of CAD-VR integration is Method 1, which involves converting CAD files into VR due to its ability to leverage both technologies' strengths while maintaining compatibility with traditional design processes.

A more refined approach to CAD-VR integration is explored by Corallo et al. (2022), where the integration is optimized for the navigation and animation of 3D-CAD models relevant to complex applications such as railway maintenance operations. This study addresses critical challenges such as interoperability between different CAD file formats, which can often hinder the seamless transition between CAD and VR environments. To overcome these issues, the researchers utilized a standardized STEP (Standard for the Exchange of Product model data) data exchange format, facilitating the smooth conversion of 3D-CAD models into the VR environment (Corallo et al., 2022). This approach is illustrated in Figure 4.

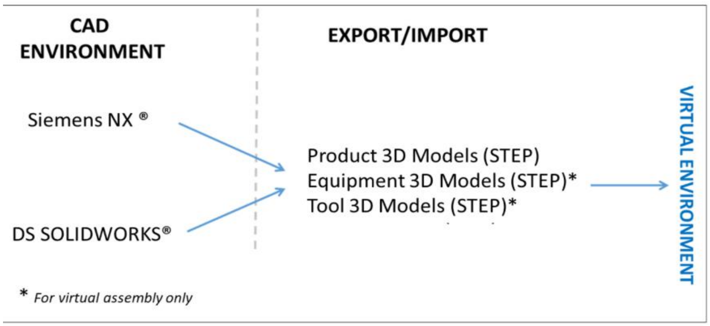

Figure 4. Software Chain of CAD-VR Integration (Corallo et al., 2022)

This software chain above provides a systematic approach to converting 3D-CAD models into VR, ensuring that the intricate details are accurately represented in the virtual environment. As shown in the figure, the STEP format plays a pivotal role in maintaining the integrity of CAD models during the transition to VR, thereby enabling more effective visualization, simulation, and ergonomic assessment (Corallo et al., 2022).

METHODS

The factors and aspects discussed in the previous sections establish a robust foundation for developing a conceptual framework that integrates mixed methods and technological tools to optimize ergonomic assessments for railway maintenance workers. The methodology adopted to achieve this is discussed in the succeeding sections.

Research Design

The framework is developed using an inductive approach, which begins with identifying research questions, followed by a structured process to address these questions. A mixed-methods design is employed, combining both quantitative and qualitative research designs with intervention through visualization. Specifically, the study adopts a concurrent triangulation design, where quantitative and qualitative data are collected and analysed independently yet simultaneously (Taherdoost, 2022).

The study applies an embedded design approach, where quantitative data is the primary source, supported by qualitative data, to merge, interpret, and draw inferences from the gathered data. This approach is illustrated in Figure 5.

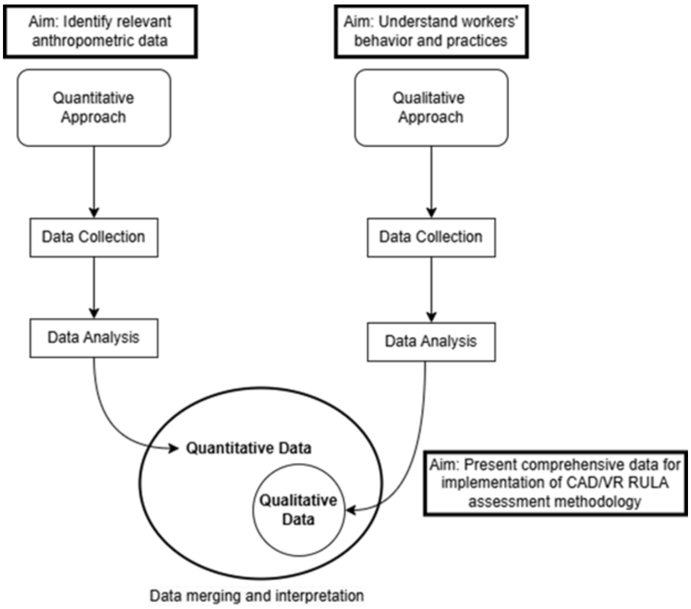

Figure 5. Research Design

Tools and Technologies

A myriad of tools and technologies are essential for implementing the proposed conceptual framework. These tools primarily support data collection and analysis procedures, enabling the acquisition of both quantitative and qualitative data for comprehensive ergonomic assessments. The essential tools include checklists recommended by the Malaysian Department of Safety and Health for physical ergonomics assessments, which provide a standardized approach to evaluating workplace risks (Malaysia D. O. S. H., 2017). Additionally, the Cornell Musculoskeletal Discomfort Questionnaire (CMDQ) is a reference tool to gather data on workers' behavior, discomfort, and attitudes toward various tasks, offering valuable qualitative insights.

For the quantitative approach, the study utilizes a series of tools to collect anthropometric data from the sampled workers. These tools are summarized in Table 1.

Table 1. Tools and Equipment

Tool	Purpose
Anthropometer	Used to measure major body dimensions such as height, arm span, and limb length.
Measuring Tape	Applied to determine circumferences of different body sections.
Stadiometer	Employed to measure both sitting and standing heights.
Weighing Scale	Used to measure body mass, from which the Body Mass Index (BMI) is calculated.

The study employs both 3D-CAD and Virtual Reality (VR) technologies to enhance risk assessment and ergonomic intervention strategies. The Computer-Aided Three-Dimensional Interactive Application (CATIA), a 3D-CAD software developed by Dassault Systèmes, is utilized for conducting comprehensive ergonomic risk assessments. Specifically, the Rapid Upper Limb Assessment (RULA) tool within CATIA is applied to evaluate ergonomic risks related to workers' upper body interactions with their workstations, identifying postural risks that could lead to musculoskeletal disorders.

The RULA assessment conducted in CATIA is further enhanced by integrating Virtual Reality (VR) to simulate and analyse workers' interactions with their workstations in real time. VR allows for a more immersive and dynamic evaluation, incorporating anthropometric data and task performance metrics. By simulating workstation dimensions and working conditions established through the RULA tool, VR provides a visual and interactive platform to understand better how workers engage with their environment, offering opportunities for immediate feedback and ergonomic improvements.

This study collaborates with STDCx and Siemens Laboratory Malaysia, which provide access to state-of-the-art VR laboratory resources, ensuring that the integration of VR technology into the ergonomic assessment process is both practical and cutting-edge.

Data Collection

The study adopts a concurrent triangulation research design, meaning quantitative and qualitative data are collected independently but simultaneously.

Quantitative Data Collection

Quantitative data is gathered from multiple sources, including workstation measurements, tooling dimensions, and anthropometric measurements from the railway maintenance workers participants in this study. The key anthropometric variables include height, weight, limb lengths, joint ranges, and body mass indices. These metrics are crucial in understanding the physical characteristics of workers, which influence ergonomic risks and intervention strategies. In addition, a structured, close-ended questionnaire, the CMDQ, is administered to quantify worker attitudes and behaviours toward their work environment and tasks, providing further insights into the relationship between worker characteristics and ergonomic challenges.

Population and Sampling

The target population for the study includes Malaysian railway maintenance workers. With over 1,600 kilometres of railway network, the Malaysian railway system was selected due to its proximity and access to critical resources pertinent to the research, such as maintenance workers and relevant workstations (Yusoff et al., 2021).

Due to two key factors, the study employs non-probability sampling, specifically convenience sampling. First, ergonomic challenges related to railway maintenance workers remain under-researched, particularly in Malaysia, despite the country's rapid rail expansion and modernization. There are also significant time and accessibility constraints. These limitations make convenience sampling practical for gathering data within the available timeframe and resources.

The sample consists of a subset of workers selected based on their access to specific workstations relevant to the study. The sample size is calculated assuming that the population size is finite (Yek et al., 2023). The equation applied to determine the sample size is:

$$Sample\ size, n = \frac{\frac{z^2 x(1-p)}{e^2}}{1+\left(\frac{z^2 x(1-p)}{e^2 N}\right)} \quad (1)$$

Information:
e =margin of error.
z =z-score of the desired confidence level.
N =population size.
p = estimated percentage of the population with the desired characteristic.

Qualitative Data Collection

Qualitative data is collected through video recordings and interviews. Detailed observations are carried out at railway maintenance workstations, focusing on factors such as posture, repetitive motions, lifting techniques, lighting conditions, noise levels, and temperature. Video recordings document and analyse these factors in real time, enabling a deeper understanding of the dynamic working environment. This is supplemented by interviews with select workers from the sample to explore behaviour and ergonomic practices in greater depth, thereby providing a richer context for interpreting the data collected from quantitative methods.

Data Analysis

Collected data is also analyzed according to the principles of concurrent triangulation design, allowing quantitative and qualitative data to be processed independently.

Quantitative Data Analysis

Quantitative data is analyzed using two essential statistical methods: descriptive and inferential statistics. Descriptive statistics summarize the dataset, clearly showing the sample's key characteristics, such as anthropometric measurements, task performance, and workstation dimensions. This initial analysis is crucial for identifying trends, variations, and patterns within the data, laying the foundation for understanding ergonomic risks (Singh & Dalpatadu, 2020).

Inferential statistics are then used to investigate relationships between variables, such as the correlation between workers' body dimensions and the likelihood of MSDs. This method supports the development of conclusions and predictions, facilitating the identification of significant ergonomic factors that affect railway maintenance workers (Singh & Dalpatadu, 2020). Moreover, inferential analysis provides critical input for the Rapid Upper Limb Assessment (RULA), guiding the prioritization of interventions based on quantitative findings

Qualitative Data Analysis

Qualitative data is analyzed through content analysis and thematic analysis. Content analysis systematically examines and codes responses from the interviews, site observations, and video recordings (Taherdoost, 2022). This technique helps identify recurring ergonomic issues, such as improper postures, repetitive motions, or suboptimal working conditions.

Thematic analysis is used to deduce the meaning behind the interview responses, focusing on workers' subjective experiences and perceptions. This approach identifies key themes and patterns, such as workers' attitudes toward tasks, ergonomic practices, and potential safety risks.

Framework Development

Framework development entails a comprehensive data integration strategy that combines quantitative and qualitative data to form a cohesive understanding of ergonomic risks and to develop targeted interventions for addressing these challenges. By synthesizing findings from both types of analyses, the study creates a robust foundation for informed decision-making in the design of maintenance workstations using 3D-CAD and VR technologies.

In this study, data integration is achieved by strategically embedding qualitative insights into a framework primarily driven by quantitative data, as illustrated in Figure 6.

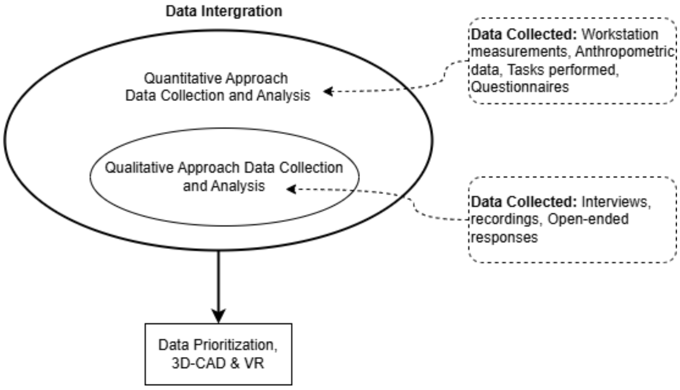

Figure 6. Data Integration Process

The figure demonstrates the embedding process, where qualitative data derived from video recordings and interviews is incorporated into a quantitative framework. This framework comprises numerical data describing workstation measurements, worker anthropometry, and task analyses. Integrating qualitative data enriches the quantitative findings by adding context and depth, enabling a more nuanced interpretation of the results. The integrated data is then systematically prioritized and interpreted to inform ergonomic design decisions in 3D-CAD and VR environments. This process ensures that ergonomic interventions are based on numerical data and responsive to the lived experiences and challenges workers face.

Ethical Considerations

Ethical considerations play a crucial role in this study, particularly concerning the integrity of the data collection process. Informed consent is obtained from all participants involved in the study to uphold ethical standards. Each participant is provided with clear and comprehensive information regarding the research's purpose, nature, and potential implications.

Furthermore, participants are made aware of their right to withdraw from the study at any time, ensuring their participation is voluntary. These ethical considerations are in coherence with the relevant frameworks adopted by the Centre for Graduate Studies (CGS) at Universiti Selangor (UNISEL), Malaysia.

RESULTS AND DISCUSSION

Implementing the processes described in the previous sections culminates in establishing a robust conceptual framework that integrates three primary components: the quantitative approach, the qualitative approach, and intervention through visualization. This framework is illustrated in Figure 7.

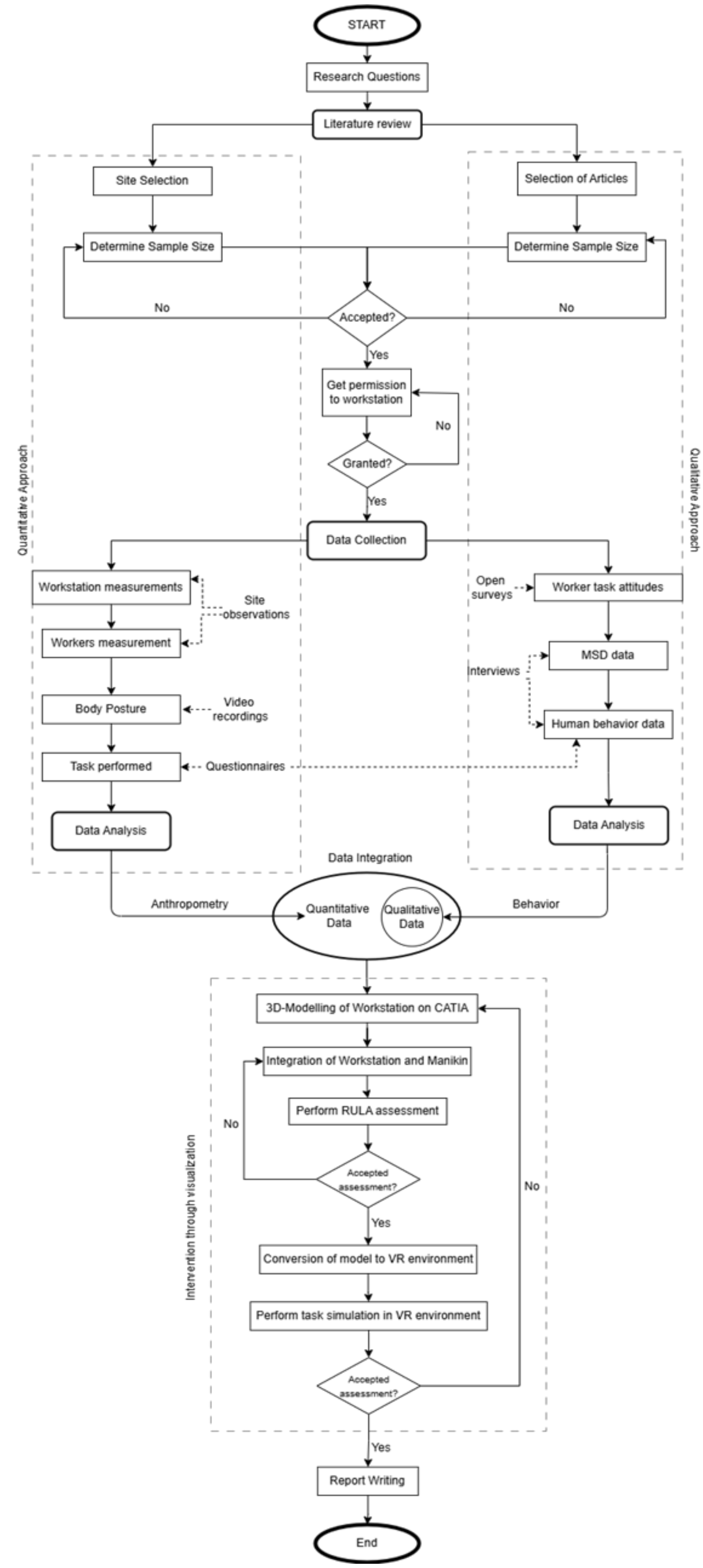

Figure 7. Conceptual Framework

The conceptual framework illustrated in Figure 7 represents a synthesis of various methodologies strategically integrated to create a systematic approach for conducting ergonomic assessments. This framework leverages the strengths of both quantitative and qualitative methods to provide a comprehensive dataset that is both objective (anthropometric data) and subjective (behavioural data). Such a holistic dataset serves as a solid foundation for identifying ergonomic challenges and formulating effective strategies for mitigating them.

Quantitative and Qualitative Integration

Quantitative data collection and analysis are enriched by qualitative insights, resulting in a nuanced understanding of ergonomic risks. For example, quantitative data, such as workstation measurements, body postures, and task characteristics, are complemented by qualitative data, including worker behaviors, attitudes, and experiences with musculoskeletal disorders (MSDs). This integration ensures that the ergonomic assessment is data-driven and grounded in the workers' lived experiences, leading to more accurate and relevant findings.

Incorporation of RULA within 3D-CAD

A vital component of this framework is the integration of the Rapid Upper Limb Assessment (RULA) tool within the 3D-CAD software, specifically CATIA. The mixed methods data informs the parameters required for RULA assessments, such as workstation dimensions, body postures, and task-specific movements. This integration allows for a detailed ergonomic evaluation within the design phase, ensuring potential risks are identified and addressed early in the process. The objective data from the RULA assessments can be cross-referenced with qualitative insights to refine ergonomic solutions further.

Virtual Reality (VR) as a Visualization Tool

The framework also incorporates Virtual Reality (VR) as a powerful tool for simulating and visualizing the interactions between workers and their workstations. VR adds a dynamic dimension to the assessment process by enabling immersive simulations where workers can interact with full-scale models of their work environments. This technology allows for real-time feedback during the assessment, providing valuable insights into how workers perceive and interact with their workstations. Such feedback is crucial for identifying potential ergonomic challenges that may not be apparent in traditional assessments.

Continuous Improvement through Iterative Design

The VR component also facilitates a continuous improvement cycle in workstation design. Feedback obtained during VR simulations can be used to refine workstation designs iteratively, ensuring that any ergonomic challenges are promptly addressed. This iterative process helps maintain a proactive approach to ergonomics, identifying and mitigating potential issues before they can affect worker health and productivity.

Novelty and Impact

The proposed framework offers a novel approach by integrating workers' behaviour and attitudes by collecting qualitative data, which complements the quantitative data. This method deviates from typical mixed-method approaches in ergonomics assessments, which often focus on comparing and contrasting qualitative and quantitative findings. The framework provides a holistic solution by "embedding" qualitative insights, such as workers' behaviours, attitudes, and perceptions, into quantitative measures of anthropometric data and workstation assessments. This dual focus addresses both objective (measurable) and subjective (experiential) challenges, creating a more comprehensive approach to understanding and mitigating ergonomic risks faced by railway maintenance workers.

Additionally, while many ergonomic practices have begun incorporating advanced technologies like 3D-CAD and Virtual Reality (VR), their integration into a unified and standardized process remains relatively underexplored. The proposed framework addresses this gap by seamlessly combining 3D-CAD and VR, leveraging their strengths in a complementary manner. Rather than using these technologies independently, the framework emphasizes their synergistic application. 3D-CAD is employed to assess ergonomic risks by evaluating workspace design and anthropometric data, while VR allows for the visualization of results and task simulations in an immersive, interactive environment.

This integration enables workers to engage actively with the workstations and tools in a virtual environment, providing valuable real-time feedback. Such interaction enhances the accuracy of ergonomic assessments and supports the development of effective intervention measures. By simulating work operations in VR, potential risks can be identified and mitigated proactively, improving worker safety and productivity in railway maintenance tasks.

CONCLUSION

This study aimed to develop a comprehensive framework to optimize ergonomic solutions for railway maintenance workers by integrating mixed methods and advanced technological tools. The framework offers a holistic understanding of ergonomic challenges by combining quantitative methods, such as structured measurements and surveys, with qualitative approaches like open-ended interviews. This dual approach captures both the measurable physical aspects of ergonomics and the subjective worker experiences, leading to a more comprehensive assessment.

The framework's strength lies in its embedded convergent design, which merges diverse data sources for a balanced interpretation of empirical and experiential inputs. This integration ensures that worker perspectives are incorporated into objective ergonomic assessments. Moreover, advanced tools, such as 3D-CAD for ergonomic modeling and Virtual Reality (VR) for task simulations and feedback, enhance the visualization and intervention processes, making the framework more interactive and participatory.

The study demonstrated that the proposed framework is well-suited for ergonomic assessments, especially in railway maintenance workstations, and that emerging technologies like VR can be used effectively to enhance ergonomic interventions. Additionally, the modular nature of the framework ensures adaptability, allowing for future technological advancements and refinements in ergonomic assessment methodologies.

Future Works

As this study forms the foundation for a broader project, future work will focus on applying the proposed framework in practical settings. A case study involving railway maintenance workers in Malaysia is planned to evaluate the framework's effectiveness in real-world applications. This will include measuring its impact on reducing ergonomic risks, specifically musculoskeletal disorders (MSD), among the workers.

Challenges, such as resource constraints and access to VR tools, may arise during implementation. Expanding the scope from predefined workstations to all areas of maintenance operations could help mitigate these challenges. Future studies will also focus on refining the framework to accommodate industry-specific needs and developing a generalized version that can be applied across sectors such as automotive, aeronautics, and shipbuilding.

These steps will validate the framework's versatility and contribute to advancing ergonomic assessment methodologies, ensuring their relevance in an increasingly technology-driven landscape.

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