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Research Article

# Mixed Methods Approach to Ergonomic Risk Assessment in Malaysian Railway Maintenance Operations

Hellstrome Young Akuma *, Nazlin Hanie Abdullah

Advanced Materials & Manufacturing Research Group, Faculty of Engineering and Life Sciences, Universiti Selangor, Malaysia

*Corresponding Author: yhellstrome@yahoo.com


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## ABSTRACT

The safety and well-being of human personnel play an increasingly important role in determining whether prescribed objectives and overall performance goals are met in work environments. Various Ergonomic Risk Assessment (ERA) methodologies are thus constantly applied to examine whether risks and hazards that can lead to musculoskeletal disorders (MSDs) are present in these environments. This is especially true in high-risk industries, such as railway maintenance, where workers are subjected to repetitive tasks that are often dynamic and complex in nature. This study, therefore, proposes a conceptual framework to assess ergonomic risk factors (ERFs) in such environments, and suggests mechanisms for intervention. To achieve this, a Cornell Musculoskeletal Discomfort Questionnaire (CMDQ) was used to collect pain and discomfort data from 27 Malaysian railway maintenance workers (n=27). This was supported by semi-structured interviews, which provided context for the numerical results and incorporated workers' perceptions of their routine tasks into the overall study design. Findings from the collected data showed that workers were often exposed to ERFs, including awkward and static postures over long periods of time. Pain and discomfort were also reported in upper body regions, including the shoulders, neck, and wrists. These results exposed the need for the incorporation of modern technological tools to support the assessment process. The proposed framework, therefore, sets a stage for the integration of Three-Dimensional Computer-Aided Design (3D-CAD) and Virtual Reality (VR) as simulation and visualization components of ERA.

**Keywords:** ergonomics, musculoskeletal disorders, railway maintenance, risk factors

## INTRODUCTION

Physical ergonomics continues to be fundamental in addressing risks and hazards that can compromize the safety and well-being of workers [1]. These risks are profound in dynamic workplaces, where personnel interact with complex machinery and systems, such as railway maintenance operations [2]. In these settings, tasks are performed in shifts during downtime periods and often have time constraints. Worker routines, therefore, involve strenuous and repetitive tasks in confined spaces, which expose them to the risk of Musculoskeletal Disorders (MSDs) [3].

Mechanisms that address challenges associated with workplace risks and hazards, such as the Ergonomic Risk Assessment (ERA) process continues to be implemented as mitigation strategies [4]. However, current approaches focus on static posture and therefore fail to capture the ever-evolving nature of risks associated with high-intensity and interactive work environments, including railway maintenance [5], [6]. This contradicts new studies that advocate for the continued evolution of assessment procedures to keep up with emerging technologies [7], [8]. It also shows that modern ergonomic approaches should not only be participatory in nature, but also be tailored to specific operations and work conditions, to avoid the pitfalls of generalisation [9].

The evolution of technology has the potential to streamline the ERA process, especially with the introduction of tools such as three-dimensional Computer-Aided Design (3D-CAD) and Virtual Reality (VR) [10], [11]. In high-risk maintenance contexts, however, this potential remains largely unrealized with such tools limited to the design phase [12], [13]. In the risk assessment process, when these tools are used, they are used independently, overlooking the benefits of a combined-integrated framework [14], [15].

There are therefore important gaps that need to be addressed. The first is that current physical assessment methods do not capture the complexity of operations involving workers performing routine tasks that are subject to complex and changing engineering systems [16], [1]. The established frameworks also either focus on the physical or behavioural dimension of ergonomics, without a consideration of applying the two cohesively to address both physical risks and how workers perceive these risks [17]. Finally, while 3D-CAD and VR technologies hold significant potential in simulating and visualizing ergonomic risks to chat intervention strategies, these tools are still not fully integrated into the existing ERA frameworks [16], [18].

To address these challenges, this study proposes a conceptual framework that considers three integrated approaches. It applies guidelines from Malaysia's Department of Safety and Health (DOSH) shown in Figure 1, to fit the ERA process to the Malaysian railway maintenance context [1]. The study also uses a mixed methods design, incorporating both quantitative and qualitative data, to ensure that both physical objective information and worker

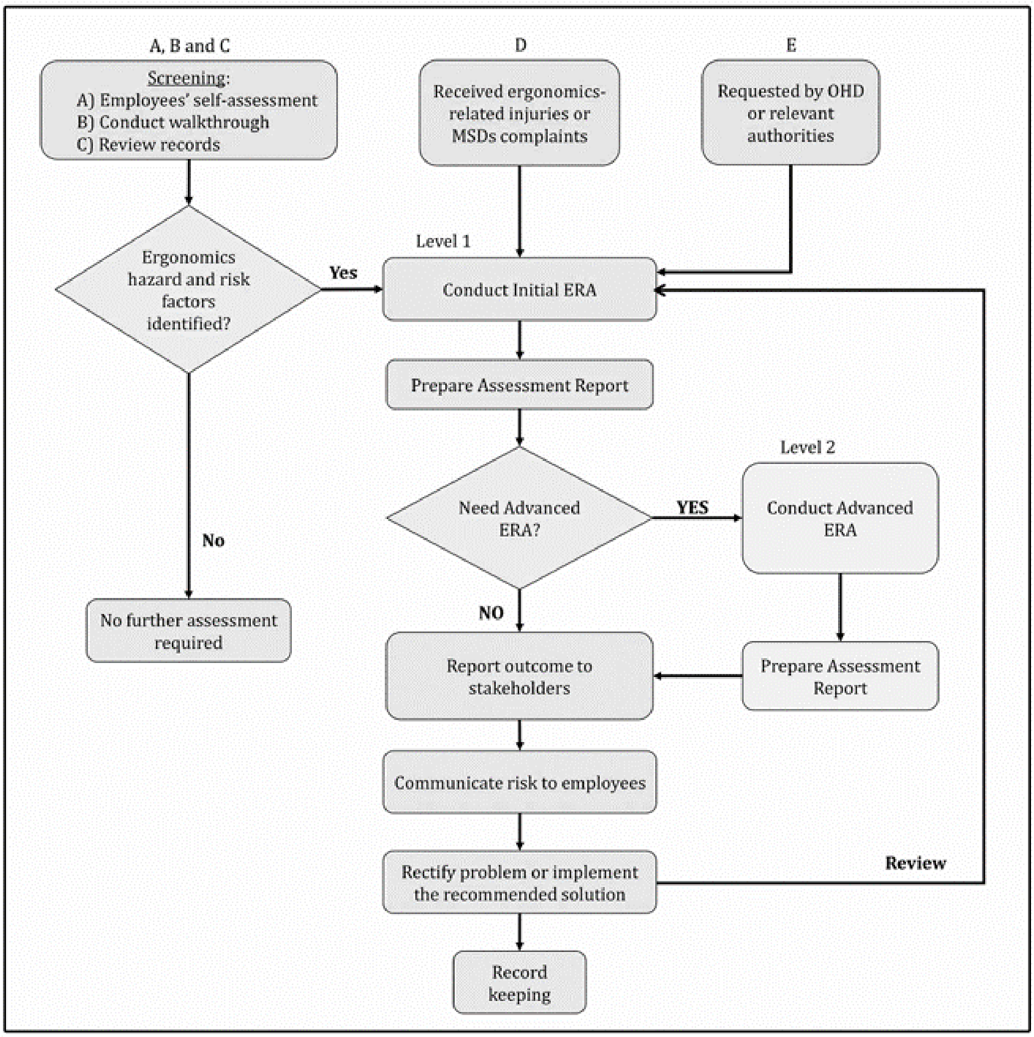


Figure 1. DOSH Risk Assessment [1]

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perceptions are used in developing the framework. Finally, the developed framework is used to verify a process that would, in future, incorporate 3D-CAD and VR as intervention tools to mitigate any assessed ergonomic risks.

The physical risk assessment model contains proactive elements, which identify ergonomic hazards before they happen, and reactive components for managing risk identified post-evaluation. Our study, therefore, proposes a new approach to risk assessment that examines railway maintenance workers' behaviours and attitudes to inform how ergonomic risk factors (ERFs) can be identified effectively. This is achieved by introducing a modular conceptual framework based on Malaysian DOSH ERA guidelines, which can provide a practical basis for adapting technological tools in the railway maintenance context. Contrary to other studies, which apply these tools and techniques independently [14], [15], our framework utilizes both the physical and behavioural dimensions of ergonomics. In addition, it lays the foundation for future research work on implementing technologies, including 3D-CAD and VR, for continuous monitoring and simulation of ergonomic risks. By so doing, the study hopes to bridge the gap between conventional and newer technology-based approaches to ERA.

## METHODS

The study's proposed framework is based on the latest guidelines provided by the Malaysian Department of Occupational Safety and Health (DOSH) [1], as shown in Figure 1. It is structured on a mixed-methods research design to optimize risk evaluation among railway maintenance workers, and culminates in a pilot study that was conducted to validate the framework's applicability.

### Research Design

An inductive research approach was applied, which began by deriving research questions from ergonomic challenges that had been observed in Malaysian railway maintenance operations. The reason for adopting this approach was that the developed framework could be informed by reliable first-hand data, and therefore, create a standardized method for integrating current assessment practices with immersive visualization tools, especially 3D-CAD and VR [4].

Using a mixed methods design also ensured that both the measurable and experiential data from the workers was examined and applied to determine ergonomic risks [19]. This involved a concurrent triangulation design, which collected and analysed quantitative and qualitative data simultaneously and independently [20]. Finally, quantitative data were complemented and contextualized by qualitative feedback using an embedded design strategy [21], [22]. This design is shown in Figure 2. The parallel data collection streams shown in Figure 2 encompass quantitative data from the Cornell Musculoskeletal Discomfort Questionnaire (CMDQ) and workstation measurements, as well as qualitative data from interviews and observations. After independent analyses, these streams were merged so that the qualitative dataset could inform how quantitative results were interpreted [23].

### Population and Sampling

A target population of Malaysian railway maintenance workers was selected for the study because of the railway sector's strategic role in national infrastructure. Malaysia currently has over 1,600 kilometres of active railway lines, which provides a suitable context for examining ergonomics for maintenance workers associated with operations in this field [24]. Determining the sample involved applying the non-probability sampling technique. This technique has some drawbacks, including sampling bias, a diminished representativeness of the population, and limited generalizability of the eventual findings [25]. For this study, the choice of this sampling technique was attributed to the following reasons [26]:

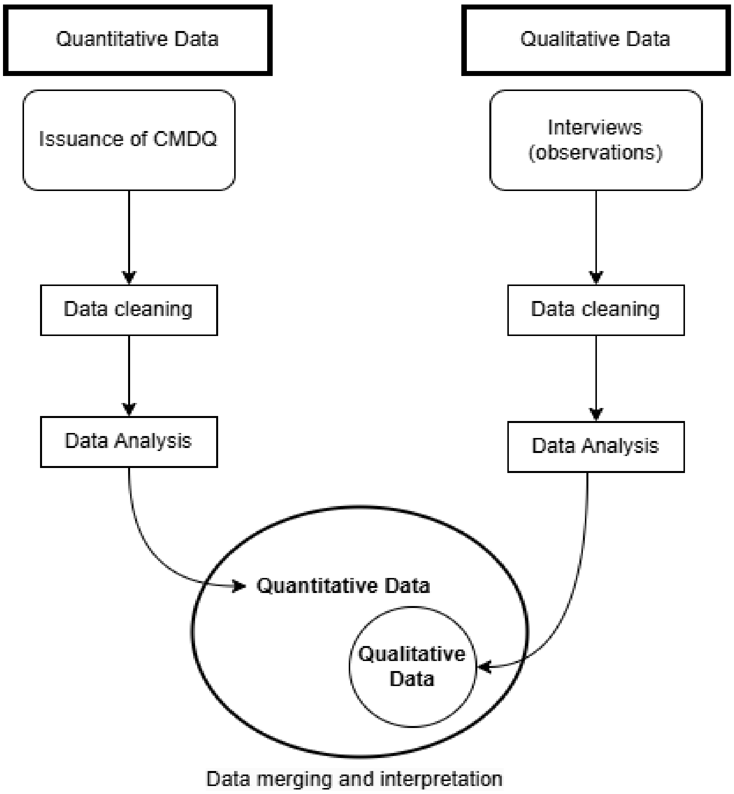


Figure 2. Research Design

1. The studies that focus on ergonomic risks faced by Malaysian railway maintenance workers are scarce, which necessitates an exploratory sampling strategy.
2. There are time constraints to complete the study, and access to the workstations is also limited, which inhibits the use of random sampling.
3. Because of the small workforce of the department under study, all available and consenting workers (N = 27) were sampled, which constituted the fully accessible population.

Participants for the study were thus drawn from the Track Inspection and Maintenance Department.

## Ethical Considerations

The Centre for Graduate Studies (CGS) at Universiti Selangor (UNISEL) provided ethical approval and oversight on the data collection process. This also involved a briefing of all the participants, including the purpose of the study, adherence to confidentiality, and their voluntary participation, as well as the right to withdraw at will.

## Tools and Technologies

Various tools were used to take required measurements and complete the necessary ergonomic assessment. The Ergonomic Risk Assessment Checklist presented in Figure 3 was used to identify hazards at the workstation, such as posture, repetition, force, and manual handling risks [1]. The Cornell Musculoskeletal Discomfort Questionnaire (CMDQ) [27] was also used to document the severity and intensity of pain or discomfort experienced by the participants, and what body regions were most affected. Because of language barriers, this questionnaire was translated to the local Malay language (Appendix A.1.). To complete the collection of workstation measurements and environmental conditions, there were also additional tools used that are described in Table 1.

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| Risk factors | Total Score | Minimum requirement for advanced assessment | Result of Initial ERA | Any Pain or Discomfort due to risk factors as found in Musculoskeletal Assessment (refer Part 3.1) (Yes/No) | Need Advanced ERA? (Yes/No) |
|---|---|---|---|---|---|
| Awkward Postures | 13 | ≥ 6 | | YES / NO<br>*If YES, please tick (√) which part of the body*<br>Neck<br>Shoulder<br>Upper back<br>Upper arm<br>Lower back<br>Forearm<br>Wrist<br>Hand<br>Hip/buttocks<br>Thigh<br>Knee<br>Lower leg<br>Feet | |
| Static and Sustained Work Posture | 3 | ≥ 1 | | | |
| Forceful Exertion | 1 | 1 | | | |
| Repetitive Motion | 5 | ≥ 1 | | | |
| Vibration | 4 | ≥ 1 | | | |
| Lighting | 1 | 1 | | | |
| Temperature | 1 | 1 | | | |
| Ventilation | 1 | 1 | | | |
| Noise | 2 | ≥ 1 | | | |

Figure 3. ERA Checklist [1]

Table 1. Tools and Equipment

| Tool | Purpose |
|---|---|
| Lux meter | Used to measure the level of light exposure within the work environment |
| Measuring Tape | Applied to determine various workstation dimensions as appropriate |
| Sound level meter | Measures the levels of noise within the work environment |
| Anthropometer | Used to measure major body dimensions such as height, arm span, and limb length. |

## Data Collection

The data collection process involved recording various risks associated with routine operations, including questionnaires and field observations, and qualitative techniques through interviews.

### *Quantitative Data*

Quantitative data was obtained from three sources:

1. Measuring the dimensions of workstations and the size of tooling used by the workers, to understand if there were any space limitations and task requirements, respectively.
2. Using the DOSH Checklist [1] to record ergonomic risk factors.
3. Collecting responses from CMDQ questionnaires distributed to the workers, which would show the levels and regions where pain and discomfort were experienced.

### *Qualitative Data*

Qualitative data was collected using two methods:

1. Videos were recorded at the workstation to capture body positions and postures of the workers as they performed their routine tasks. The recordings also captured environmental conditions, including noise, lighting and vibration.

Semi-structured Interviews, which were conducted to explore workers' attitudes and how they cope with any pain or discomfort during task execution. The interview guide was informed by the CMDQ and the Generic Work Behavior Questionnaire (GWBQ) developed by 6icho net al. [28]. Appendix A.2 shows an excerpt of the interview questions used and their responses.

## Data Analysis

### *Quantitative Analysis*

To analyze numerical data, the study used IBM SPSS Statistics software, which performed data cleaning and statistical analysis. This was achieved as follows:

1. Utilizing descriptive statistics to provide an overview of the dataset and show trends such as central tendency, mean, median, and variability, which would be useful in contextualizing the differences and similarities in the numeric data from the workers [29]. These statistics would thus inform key pain and discomfort characteristics associated with CMDQ, including affected body regions, severity and frequency.
2. Using inferential statistics, and the Chi-Square Test in particular [30], to examine the relationship between affected body regions and whether there was a likelihood of musculoskeletal disorders (MSDs) occurring. This was accomplished through the following formula.
3. Applying inferential statistics to show potential relationships between variables, such as correlations between body regions and the likelihood of musculoskeletal disorders (MSDs). For this study, the categorical variables were the affected body regions and the pain levels experienced. To accomplish this, a Chi-Square test was conducted using the following formula.

$$X^2 = \sum \frac{(O_{ij} - E_{ij})^2}{E_{ij}} \tag{1}$$

   where
   $O_{ij}$: is the observed frequency in the i-th row and j-th column, and
   $E_{ij}$: is the expected frequency under the null hypothesis, determined as

$$E_{ij} = \frac{(Row\ Total\ x\ Column\ Total)}{Grand\ Total} \tag{2}$$

4. Using the Rapid Upper Limb Assessment (RULA) [31] process to quantify risks associated with the workers' postures as they performed their tasks (Appendix A.3.).

### *Qualitative Analysis*

During the study, analysing the qualitative data involved identifying themes that appeared repetitively throughout the interview transcripts [32]. Table 2 shows the appropriate themes which were guided by frameworks from both the CMDQ and GWBQ questionnaires.

Table 2. Theme Categories for Qualitative Data

| **Category** | **Description** |
|---|---|
| Regional Pain | Frequent reports of shoulder discomfort |
| Cognitive Fatigue | Losing focus, especially during night shifts |
| Behavioral Coping | Informal breaks and posture adjustments |
| Temporal Factors | Increased discomfort during extended shifts |
| Underreporting | Hesitation to disclose symptoms |
| Improvement Ideas | Suggestions for adjustable tools, training |

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The categories in Table 2 were applied to guide the semi-structured questions presented to the interviewee with the aim of establishing a relationship between the observed and collected numerical data and workers' attitudes within the context of their work environment and tasks performed.

## Conceptual Framework

The final framework, shown in Figure 4, was constructed using the embedded mixed-methods approach, with quantitative data forming the core (workstation dimensions, CMDQ results) and qualitative data embedded to provide interpretive context. The process depicted in the framework is a phased approach to risk assessment that

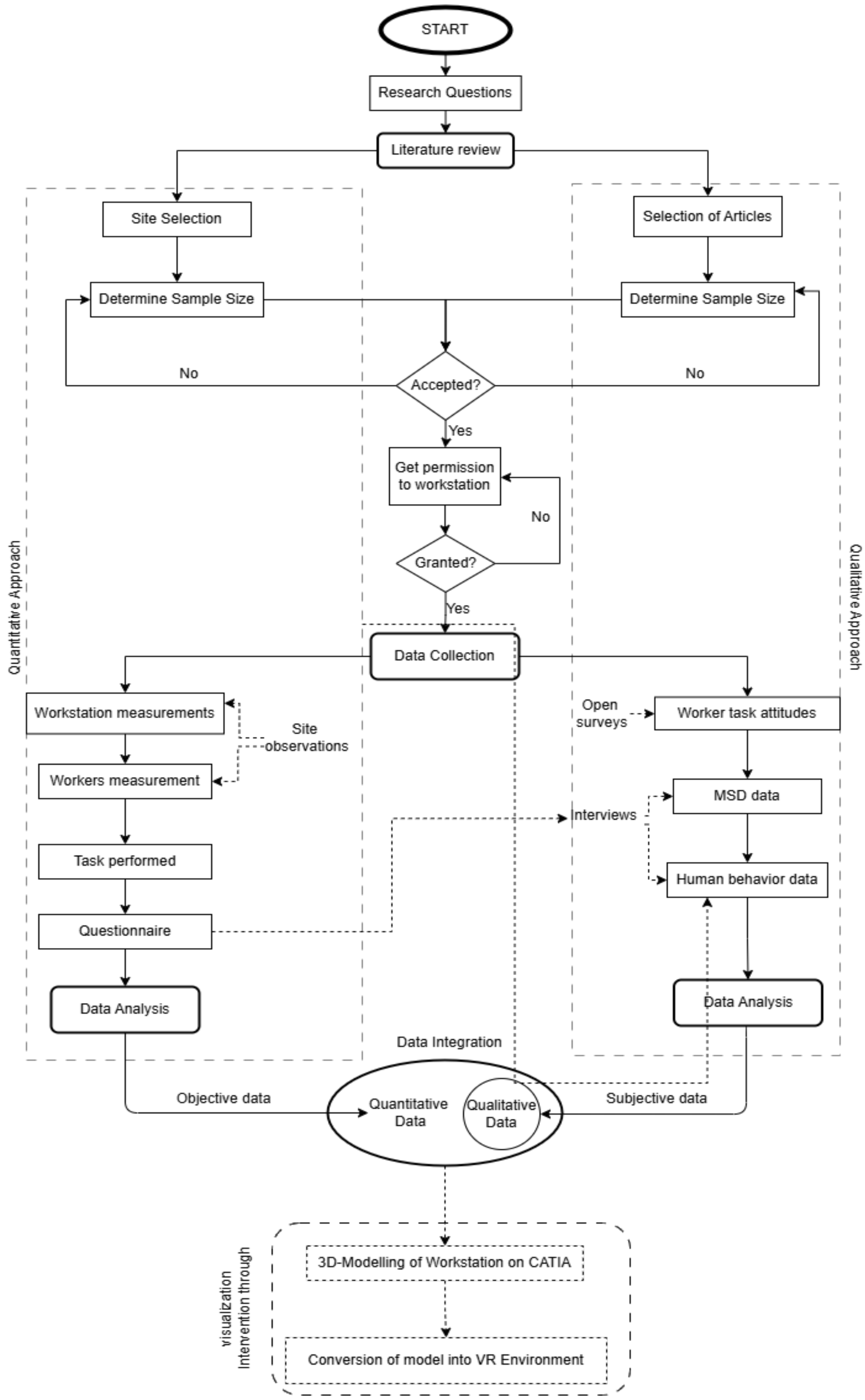


Figure 4. Conceptual Framework

highlights crucial steps needed to synthesize robust findings for ergonomic intervention. One arm of this approach applies quantitative methods of data collection and analysis, while the other takes qualitative data and embeds it into the numeric analysis. The framework also creates an extra, albeit modular dimension where 3D-CAD and VR can be integrated for simulation and visualization, respectively, to enhance feedback and intervention mechanisms.

## RESULT AND DISCUSSION

The proposed framework was applied to examine ergonomic risk factors (ERFs) that participants of the study were exposed to. Results from these findings, including their demographic profiles, the severity of pain during task execution, and how they perceive their work, are presented in the following sections.

### Demographic Characteristics

Table 3 shows a demographic summary of the 27 maintenance workers who were surveyed through the Cornell Musculoskeletal Discomfort Questionnaire (CMDQ). The results from the survey are broken down into various categories, including age, gender, job role, work experience, and work schedule. Many of the workers sampled were either between 30 and 49 years (56%) or 40 to 49 years (30%), which shows a middle-aged workforce. These findings can be correlated with the established average age of about 39 years and a standard deviation of 7.4 years, values that reinforce the central tendency notion because most of the workers are closer to the median age.

Table 3. Demographic Summary

| Demographic Variables | Frequency | Percentage |
|---|---|---|
| ***Age (Years)*** | | |
| 20-29 | 1 | 4% |
| 30-39 | 15 | 56% |
| 40-49 | 8 | 30% |
| 50-59 | 3 | 11% |
| Total | 27 | 100% |
| Mean | **39.31** | |
| Standard deviation | **7.39** | |
| ***Gender*** | | |
| Male | 27 | 100% |
| Female | 0 | 0% |
| ***Job Role*** | | |
| General Maintenance | 1 | 4% |
| Heavy Machinery Operator | 19 | 70% |
| Supervisor | 1 | 4% |
| Technician | 6 | 22% |
| ***Working Experience*** | | |
| Below 10 | 2 | 7% |
| 10-20 | 22 | 81% |
| 20 and above | 3 | 12% |
| ***Work Schedule*** | | |
| Shift work | 18 | 66% |
| Non-shift | 9 | 33% |
| Morning | 5 | 19% |
| Afternoon | 9 | 33% |
| Night | 9 | 33% |
| Flexible | 4 | 15% |

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Table 4. Tamping Machine Task Summary

| Description | Task Exposure |
|---|---|
| 1. One or two workers sit in a cabin of the tamping machine and control various instruments to ensure railway tracks are aligned vertically and horizontally.<br>2. The workers also use on-board instruments to monitor the track geometry and ballast levels.<br>3. The operators have to constantly communicate with ground personnel performing ballast regulation.<br>4. The operators use both their hands and feet to control onboard instruments for a seamless operation. | • Shift Duration: 4 hours<br>• Tool used: 150g (Walkie-talkie)<br>• Working height: Elbow/shoulder height |

Table 5. Advanced ERA Summary

| Work Activity | Evidence of MSD | Risk Factors | Method Used |
|---|---|---|---|
| Operating tamping machine controls on rail tracks | Neck, shoulder, upper arm, lower arm, wrist, trunk | • Awkward posture<br>• Static/sustained posture | Rapid Upper Limb Assessment (RULA) |
| **Outcome** | **Existing Control Measures** | **Short-Term (Corrective)** | **Long-Term (Preventative)** |
| Low to medium risk: Action level = 4 | NA | • Reviewing the workstation layout<br>• Ergonomic training for posture and body mechanics | Implementation of current technology tools, such as VR, for continuous ergonomic intervention |

Survey results also showed that all the workers in the study were male. This corroborates Hamid et al.'s [33] findings that showed the railway maintenance sector is dominated by male roles. From the workers sampled, a significant majority, at 66% operate heavy machinery. This confirms the need for ergonomic intervention since such job roles tend to have a higher exposure to physical strain, which can lead to MSDs. In terms of work experience, the results showed a highly experienced workforce with 81% of the workers serving for more than 10 years, and a further 12% having more than 20 years' worth of experience. Most of these workers (66%) also work in shifts, either in the afternoon or at night, which can exacerbate fatigue beyond the detectable physical risks.

## Ergonomic Risk Factors

The ERFs summarized in Table 4 were identified by conducting field observations at the Tamping Machine workstation. The tamping machine operator performed their tasks from a sedentary position throughout their shift. Most of the tasks were repetitive in nature and involved moving their upper body, including the shoulder, back and wrists. This is summarized by an initial ERA, which is included in Appendix A.3. The findings of a sustained posture presented a moderate ergonomic risk and prompted an advanced ERA, based on the following observed results [1].

1. The worker was in a static position for more than 2 hours of the operation
2. The worker was in a seated position with minimal movement for more than 30 minutes continuously.

In alignment with Malaysia DOSH guidelines [10], conditions met the criteria for an advanced Rapid Upper Limb Assessment (RULA). The steps for the RULA are included in Appendix A.4. Consequently, Table 5 shows a summary of the advanced ERA. The results in Table 5 show evidence of musculoskeletal disorders (MSDs) in the neck, shoulder, and wrist etc., compounded by risk factors such as awkward and static/sustained posture. Consequently,

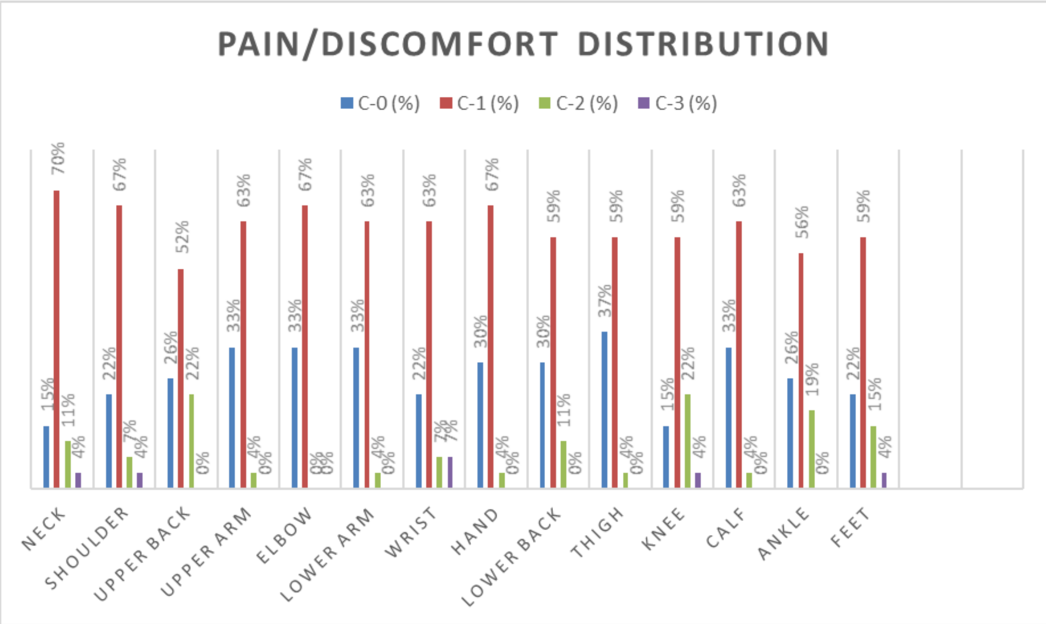


Figure 5. CMDQ Body Pain Frequency Distribution

the RULA assessment outcome is a score of 4, which shows medium risk and intervention requirements. These results indicate the relevance of reviewing and optimizing the pertinent workstation using digital tools, such as 3D-CAD modelling, and incorporating VR technology as a long-term strategy in the ERA framework of railway maintenance workers.

## Musculoskeletal Discomfort

Figure 5 presents CMDQ results indicating reported discomfort by body region. The frequency distribution of pain in different body parts among the respondents reveals that mild discomfort (C-1) was the most commonly reported pain intensity, affecting 60–95% of workers across all upper body regions. This suggests that while most tasks do not cause acute pain, prolonged exposure to ergonomic stressors leads to chronic low-grade strain. On the other hand, the cases for moderate pain (C-2) were 5-30%, while severe pain (C-3) was less frequently reported. The study also used a Chi-Square test for independence to determine if specific body regions were more prone to severe pain than others, as shown in Table 6.

The analysis found no statistically significant relationship between body region and "No Pain" ($p = 0.929$) or mild pain ($p = 1.000$). However, moderate pain (C-2) approached significance ($p = 0.095$), which is an indication that certain body regions, may be exposed to medium pain and discomfort more than others. Finally, the p-value for severe pain (C-3) is relatively high at 0.474. This indicates that there is no sufficient evidence to associate severe pain and particular body regions, a finding that could be attributed to the influence of other factors that may lead to localized pain. Figure 6 offers a visual illustration of the chi-square test.

Table 6. Chi-Square Test Summary

| Pain Level | Chi-Square | P-Value |
|---|---|---|
| C-O | 6.43 | 0.929 |
| C-1 | 1.37 | 1.000 |
| C-2 | 20.00 | 0.095 |
| C-3 | 12.67 | 0.474 |


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| Body Part | C-0 | C-1 | C-2 | C-3 |
|---|---|---|---|---|
| Neck | -1.21729 | 0.559085 | 0.267261 | 0.872872 |
| Shoulder | -0.47633 | 0.314485 | -0.35635 | 0.872872 |
| Upper Back | -0.10585 | -0.66391 | 2.13809 | -0.65465 |
| Upper Arm | 0.635107 | 0.069886 | -0.97996 | -0.65465 |
| Elbow | 0.635107 | 0.314485 | -1.60357 | -0.65465 |
| Lower Arm | 0.635107 | 0.069886 | -0.97996 | -0.65465 |
| Wrist | -0.47633 | 0.069886 | -0.35635 | 2.400397 |
| Hand | 0.264628 | 0.314485 | -0.97996 | -0.65465 |
| Lower Back | 0.264628 | -0.17471 | 0.267261 | -0.65465 |
| Thigh | 1.005587 | -0.17471 | -0.97996 | -0.65465 |
| Knee | -1.21729 | -0.17471 | 2.13809 | 0.872872 |
| Calf | 0.635107 | 0.069886 | -0.97996 | -0.65465 |
| Ankle | -0.10585 | -0.41931 | 1.51448 | -0.65465 |
| Feet | -0.47633 | -0.17471 | 0.890871 | 0.872872 |

Figure 6. Chi-Square Residual Heat Map

Figure 6 contextualizes the observed *p*-values. There are several body regions with positive deviations, including the wrist, the upper back, and the knee, and they are therefore most susceptible to injury. Conversely, regions such as the elbow and upper arm have a negative deviation and are therefore less prone to risk of injury.

## Worker Behavior and Attitude

Several open-ended questions were also presented to the worker manning the tamping machine workstation, as shown in Appendix A.2. These questions assessed how they perceive risks associated with their workplace and task execution. A sample of the responses is presented in Table 7.

The themes presented in the table informed the development of a matrix, which was applied to align the reported levels of pain and various body regions, as shown in Appendix A.5. Results indicated that certain body regions were more prone to physical strain than others, as summarized in Table 8. It shows that the wrist, neck, knee, and feet were the body regions that were most susceptible to pain and/or discomfort, with significantly high combined values for C-2 and C-3. These findings support the incorporation of themes including regional pain, temporal risk factors, and suggestions from the workers. Table 9 further shows the causes that were established, matching these themes and based on the interviews conducted during the study.

Table 7. Thematic Analysis Summary

| Theme | Explanation | Sample quote from participants |
|---|---|---|
| Regional Pain | Shoulder strain from the overhead panel | "In most cases, I lean forward and raise my shoulders to gain access…" |
| Cognitive Fatigue | Losing focus | "Towards the end of my shift, I feel tired from doing the same things." |
| Behavioral Coping | Taking unscheduled breaks | "Sometimes I need to take a break, although not part of the schedule" |
| Temporal Factors | Night shifts and discomfort | "The night shift can increase my strain (on my back), especially because there is no movement" |
| Underreporting | Reluctance to report pain | "I don't want to seem like I'm complaining" |
| Improvement Ideas | Adjustable controls, simulator | "Better seat, maybe adjustable controls…" |

Table 8. Thematically Strong CMDQ Areas

| Body Region | Total (C-2 + C-3) | Key Themes Supported |
|---|---|---|
| Wrist | 4 | Ergonomic Stressors, Worker Suggestions |
| Neck | 4 | Regional Pain, Ergonomic Stressors |
| Knee | 7 | Temporal Risk, Behavioural Adjustments |
| Feet | 5 | Temporal Risk, Regional Pain |

Table 9. Work Environment – Pain Mapping

| CMDQ Hot Zone | Pain Severity (C-2/C-3) | Linked Work Tasks | Environmental/Design Contributor | CAD-VR/Audit Insight |
|---|---|---|---|---|
| Wrist | Moderate–Severe (4 cases) | Operating overhead or side controls | Awkward control positioning above shoulder height | Simulate ergonomic reach; adjust panel angle/height |
| Neck | Moderate–Severe (4 cases) | Looking up at panels or down at ballast/track | Fixed head position due to machine posture or visual demands | Use head-tracking data in VR to improve screen alignment |
| Knee | Moderate–Severe (7 cases) | Long seated work, limited leg movement | Inflexible seating, cramped foot clearance | Audit legroom and allow for active seating configuration |
| Feet/Ankles | Moderate–Severe (5 cases) | Seated with heels down for long durations | Flat seat base, static posture, limited foot motion | Simulate seated duration; test pedal/resting foot options |
| Lower Back | Moderate (3 cases), rich qualitative data | Seated operation, minor twisting movements | Poor lumbar support, rotational controls, vibration | Track seat load/displacement in CAD; assess vibration isolation |

The results presented in Table 9 show that there are regions which, while being underreported from the CMDQ responses, were confirmed as being affected by pain or discomfort during the interviews. For instance, in the CMDQ responses, only five and three respondents reported mild discomfort in the feet and lower back regions, respectively. However, during interviews, the workers confirmed that they experienced substantial pain in these regions owing to the layout and location of workstation controls. The discrepancies can be tied to themes including cognitive fatigue, behavioral adjustments, and worker suggestions [31]. This shows that most workers underreport their pain and discomfort, which is also evident throughout the data collection process of the CMDQ [31].

From the findings, it is clear that there is a need to improve workstation layouts and synthesize better interface ergonomics. Beyond physical design, introducing practices that promote mobility could alleviate recurrent strain patterns. The developed framework thus presents a solid foundation upon which technological tools can be applied to improve the relevant workstation(s). This could be achieved by using tools such as CATIA-based RULA and VR to iteratively modify and validate workstations

## Novel Contributions and Practical Implications

The presented framework offers several contributions to ergonomics, particularly in railway maintenance and similar industries with high-risk work environments:

- The framework embeds qualitative insights directly into quantitative data, rather than juxtaposing the two methods as is the norm. This ensures that the workers' experiences inform any ergonomic intervention planning.

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- While CAD and VR tools are often used independently to alleviate ergonomic risks, this study proposes a framework where these tools can be complementary. This entails a unified assessment process that leverages CAD for precise modelling and VR for immersive worker feedback [14]. For instance, a study by Chen [3] identified limitations in using VR for routine ergonomic assessment. Some of these gaps can be addressed using the proposed framework.
- By enabling digital simulation and therefore predictive modelling, the framework establishes a basis for ergonomic risks and hazards to be identified and resolved before the deployment of physical workstations. This would reduce the incidence of MSDs [10], [34].
- Finally, this work can advance the knowledge of ergonomic risk assessment, particularly in understudied sectors, including railway maintenance in particular, and high-risk work environments in general.

## CONCLUSION

By applying guidelines from the Malaysian Department of Occupational Safety and Health (DOSH), the study developed a conceptual framework to identify ergonomic risk factors (ERFs) among railway maintenance personnel. The framework determined that risks, including awkward posture and prolonged sedentary positions, were prevalent. This was supported by results from a CMDQ survey and interviews, which showed MSD risks in the workers' upper body regions, including the neck, shoulders, upper back and wrists. In addition to contextualizing the numeric data, findings from the interviews also informed the study on appropriate intervention measures, namely the rescheduling of shift work and repositioning of crucial controls at the workstation. This thus confirms the emerging need to incorporate simulation tools such as 3D-CAD and visualization through VR, as feedback and intervention mechanisms. Although the study was hindered by a relatively small sample size (N=27), which necessitated convenience sampling due to time and accessibility constraints, these limitations are acceptable in this context. This is especially because the study is the initial phase of broader research, and therefore provides a basis for further enquiry. Future research will incorporate empirical behavioral data from the Generic Work Behavior Questionnaire (GWBQ) and apply mathematical modelling to strengthen the statistical robustness of findings. This next phase will also include 3D modelling of the identified workstation and the deployment of VR for participatory, iterative workstation redesign. The developed framework can thus be potentially used in broader contexts with similar high-risk operations, including the automotive, aerospace and shipbuilding sectors.

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## CONFLICT OF INTEREST

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## DATA AVAILABILITY STATEMENT

Due to privacy restrictions, the data are not publicly available. De-identified data may be available from the corresponding author upon reasonable request.

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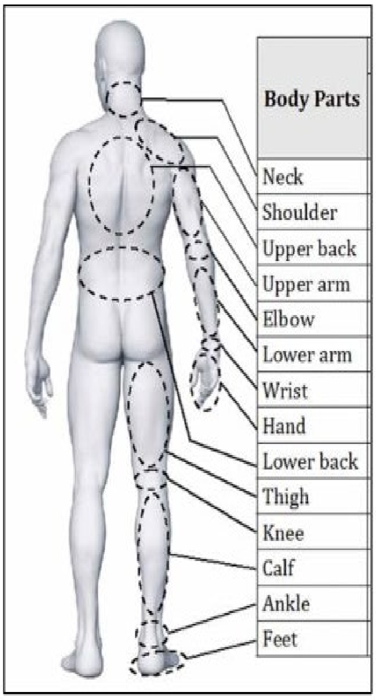
# APPENDIX

## A.1. Cornell Musculoskeletal Discomfort Questionnaire




| Body Region<br><br>*Bahagian badan* | C-1 | C-2 | C-3 |
|---|---|---|---|
| | General fatigue or mild discomfort in localized area **only during work, or subsides within 14 days.**<br><br>*Keletihan umum atau ketidakselesaan ringan di kawasan tertentu* ***hanya semasa bekerja, atau reda dalam tempoh 14 hari.*** | Persistent pain lasting **more than 14 days, but less than 3 months.** May start to affect work performance and daily activities<br><br>*Kesakitan berterusan yang dihadapi* ***lebih daripada 14 hari tetapi kurang daripada 3 bulan.*** *Mula menjejaskan prestasi kerja dan aktiviti harian.* | Pain at **all times lasting for more than 3 months.** Require a longer Medical Certificate (MC). Affects work performance and daily activities<br><br>*Kesakitan yang* ***berterusan sepanjang masa melebihi 3 bulan.*** *Memerlukan Sijil Sakit (MC) yang lebih panjang. Menjejaskan prestasi kerja dan aktiviti harian.* |
| Neck<br>*Leher* | | | |
| Shoulder<br>*Bahu* | | | |
| Upper Back<br>*Bahagian belakang atas* | | | |
| Upper Arm<br>*Lengan atas* | | | |
| Elbow<br>*Siku* | | | |
| Lower arm<br>*Lengan bawah* | | | |
| Wrist<br>*Pergelangan tangan* | | | |
| Hand<br>*tangan* | | | |

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### A.1 Cornell Musculoskeletal Discomfort Questionnaire (cont.)

| | | | | |
|---|---|---|---|---|
| | Lower back<br>*Bahagian belakang bawah* | | | |
| | Thigh<br>*Paha* | | | |
| | Knee<br>*Lutut* | | | |
| | Calf<br>*Betis* | | | |
| | Ankle<br>*Buku Lali* | | | |
| | Feet<br>*kaki* | | | |

### A.2. Semi-structured Interview Questions and Responses

1. **Can you describe which parts of your body feel the most discomfort during or after your shift?**

**Rationale:** CMDQ- aligned regional pain

**Response:**

*"By the end of my shift, my lower back and right shoulder usually ache the most. The tamping machine requires a lot of seated posture with minor twisting movements, especially when operating the side controls. There is also some vibration as you can see. The strain tends to build up over time."*

2. **How often does this discomfort affect your ability to concentrate or stay alert while performing your tasks?**

**Rationale:** Relates physical discomfort with cognitive fatigue/behaviour

**Response:**

*"When my back pain flares up, I notice I zone out more easily. For example, as I am checking ballast levels, I may need my supervisor to double-check. Sometimes its hard to concentrate when feeling uncormfortable."*

3. **Have you found yourself needing to take unscheduled breaks, or adjusting your work pace due to pain or fatigue?**

**Rationale**: Behavioural adjustments (GWBQ) prompted by physical strain (CMDQ)

**Response:**

*"Yes, our work is done at night and if you spend more than two hours on the machine, seated, you want to stand up and stretch. Although there are no scheduled breaks, we do so sometimes."*

4. **How do your workstation setup or tools contribute to any physical strain you experience?**

**Rationale:** Ergonomic risk factors and the potential for CAD-VR Integration

**Response:**

*"For me the overhead controls can be difficult especially towards the end of the shift, when the shoulders get tired. I spend a lot of time leaning forward either to look outside or to reach upper controls which can be a problem. An adjustable control panel would be beneficial."*

5. **Do you find it difficult to stay motivated or feel energetic toward the end of your shift? If so, why?**

**Rationale:** GWBQ Motivational fatigue, can affect behavior

**Response:**

*"Usually by the third hour, I just want to stop and take a break. Repeating the same thing for a period of time can get boring and also make you want to change position because of discomfort. You feel like you're running out of gas, even if you didn't do any heavy lifting."*

6. **Are there specific tasks or times of day when you notice your discomfort is more severe?**

**Rationale:** Temporal and task-based ergonomic risk profiles.

**Response:**

*"Because the shift is during night-time, yes. Being seated for long periods with minimal movement make it worse. The lack of movement stiffens my back and the back of my feet (heels) quite much."*

7. **Have you ever reported any of these ergonomic concerns to supervisors or team leads? If not, what holds you back?**

**Rationale:** Organizational framework to proactive risk identification and intervention

**Response:**

*"I've mentioned it casually to colleagues, but never filed a formal report. The perception is that discomfort is 'part of the job,' and I don't want to seem like I'm complaining.*

8. **In your opinion, what improvements could be made to reduce physical strain and fatigue in your role?**

**Rationale:** Human-centered design insights to inform CAD-VR integration

**Response:**

*"A better seat, maybe adjustable controls, would probably help. Some of the systems we use are also a bit dated, we have a simulator but we only use it during training"*

### A.3 Initial Ergonomic Risk Assessment Summary – Tamping Machine Workstation

**Observed Ergonomics Risk Factors**

| Ergonomics risk factors (ERFs) | Catalyst (long duration or repetition) | Ergo concern score (1 – 10) | Body parts involved |
|---|---|---|---|
| Forceful exertions | - | - | |
| Poor postures | Repetition | 3 | Shoulder<br>Neck<br>Wrist<br>Upper back<br>Lower back<br>Lower leg |
| Static loading/posture | Seated posture | 2 | Arm/wrist<br>Legs |
| Contact stress | - | - | |
| Vibration | - | - | |
| Lighting | - | - | |
| Temperature | - | - | |

**Musculoskeletal Assessment**

| Body Part affected | C1/ C2/ C3 |
|---|---|
| Neck | C1 |
| Shoulder | C1 |
| Upper back | C1 |
| Lower back | C1 |
| Upper arm | C1 |
| Forearm | C1 |
| Wrist | C1 |
| Hand | C1 |
| Hips/buttocks | - |
| Thigh | - |
| Knee | - |
| Lower leg | C1 |
| Feet | - |

| Require Advanced ERA? | Recommendations |
|---|---|
| YES | • Conduct an advanced ERA<br>• Introduce micro breaks<br>• Review control layout<br>• Continuous monitoring of noise and vibration levels<br>• Provide ergonomic training |

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| Observed Ergonomics Risk Factors | | | | Musculoskeletal Assessment | Require Advance d ERA? | Recommendations |
|---|---|---|---|---|---|---|
| Ventilation | - | - | | | | |
| Noise | - | - | | | | |
| Combination of ergonomics risk factors | - | - | | | | |

### A.4 Rapid Upper Limb Assessment Procedure

**Section A: Arm & Wrist Analysis**

Step 1: Locating the Upper arm position

A **+4 score** is applied because the upper arm position of the operator extends beyond 90 degrees when operating the overhead panel.

Step 2: Locating the lower arm position

A **+2 score** is given for the lower arm position which extends less than 60 degrees in all directions.

Step 3: Locating the wrist position

The wrist score is **+2** because the wrist flexes less than 15 degrees, and an extra **+1** because the ulnar deviates. The total wrist score is **+3.**

Step 4: Determining the amount of wrist twist

This score is **+1** because the wrist is twisted only to the mid-range.

Step 5: Determining the Posture Score

Based on the RULA worksheet, these values give an aggregated posture score of **Four (4).**

Step 6: Determining Muscle Use Score

The tamper operator's posture is sustained for more than 10 minutes and involves actions repeated 4 times per minute. The muscle use score is therefore **+1.**

Step 7: Determining the force/load score

The worker interacts with a load that is less than 4.4 lbs intermittently. The force/load score is therefore **0.**

Step 8: Determining the wrist/arm score

Compiling the values from steps 5 to 7 gives a total wrist/arm score of **5** as follows:

$$posture\ score\ (4) +\ Muscle\ use\ score\ (1) + \frac{Force}{load} score\ (0) = \boldsymbol{Wrist\ \&\ arm\ score\ of\ 5}$$

**Section B: Neck, Trunk and Leg Analysis**

Step 9: Locating the neck position

This value is determined to be **+2** because the worker moves the neck between 10-20 degrees.

Step 10: Locating the trunk position

The observed trunk position is 0-20 degrees with no twists or side bending, and therefore the score is determined to be **+2.**

Step 11: Determining leg positioning

The legs and feet of the worker are sufficiently supported, giving a score of **1.**

Step 12: Determining the posture score

Based on the RULA worksheet, the values in the steps above give an aggregated posture score of **two (2).**

### A.4 Rapid Upper Limb Assessment Procedure (cont.)

Step 13: Adding the Muscle score

The worker is observed to repeat various actions pertinent to the neck and trunk, more than 4 times per minute. The muscle score is therefore **+1.**

Step 14: Adding Force/load score

There is no load observed pertinent to the neck and trunk body regions of the worker. The force/load score is therefore **0.**

Step 15: Determining the neck, trunk and leg score

Compiling the values from steps 12 -14 gives a total neck, trunk and leg score of **3**, as follows:

$$posture\ score\ (2) +\ Muscle\ use\ score\ (1) + \frac{Force}{load} score\ (0) = \boldsymbol{Neck, trunk\ and\ leg\ score\ of\ 3}$$

**Final RULA Score**

The final step is determining the final RULA score, which is obtained from the pertinent RULA worksheet by inserting the final scores from the two sections above. The wrist/arm score is 5, whereas the neck, trunk and leg score is 3. This gives a final RULA score of **Four (4).**

### A.5 CMDQ-Based Thematic Matrix

| Body Part | C-2 (Moderate) | C-3 (Severe) | Related Theme(s) | Interpretation |
|---|---|---|---|---|
| **Neck** | 3 | 1 | Regional Pain, Ergonomic Stressors, Worker Suggestions | Consistent with reports of strain from awkward control panel positions and sustained posture. |
| **Shoulder** | 2 | 1 | Regional Pain, Behavioral Adjustments, Ergonomic Stressors | Suggests repetitive or static shoulder use (e.g., reaching), possibly due to machine operation. |
| **Upper Back** | 6 | 0 | Regional Pain, Temporal Risk Factors | Moderate discomfort suggests poor posture; possibly worsens over longer shifts. |
| **Upper Arm** | 1 | 0 | Minimal CMDQ support | Not a prominent area of reported strain, possibly incidental. |
| **Elbow** | 0 | 0 | No CMDQ support | Not thematically linked; likely low ergonomic relevance here. |
| **Lower Arm** | 1 | 0 | Weakly supports Ergonomic Stressors | May contribute to wrist/hand issues; not a standalone risk area. |
| **Wrist** | 2 | 2 | Ergonomic Stressors, Regional Pain, Worker Suggestions | Wrist strain supports themes related to tool/machine design (e.g., overhead control usage). |
| **Hand** | 1 | 0 | Weak link to themes | Minimal CMDQ pain; no clear thematic correspondence. |
| **Lower Back** | 3 | 0 | Regional Pain, Cognitive Fatigue, Behavioral Adjustments, Worker Suggestions | Frequently referenced in interviews; CMDQ scores support as a central strain site. |

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**A.5 CMDQ-Based Thematic Matrix (cont.)**

| Body Part | C-2 (Moderate) | C-3 (Severe) | Related Theme(s) | Interpretation |
|---|---|---|---|---|
| **Thigh** | 1 | 0 | Minimal CMDQ support | Not reported thematically—likely from prolonged sitting. |
| **Knee** | 6 | 1 | Temporal Risk Factors, Behavioral Adjustments | Indicates static posture or prolonged immobility contributing to discomfort. |
| **Calf** | 1 | 0 | Weak support | May relate to "back of feet" discomfort mentioned, but not directly evident. |
| **Ankle** | 5 | 0 | Temporal Risk Factors, Behavioral Adjustments (limited) | Moderate pain suggests strain from prolonged seated posture. |
| **Feet** | 4 | 1 | Temporal Risk Factors, Regional Pain | Matches interview reference to heel discomfort during long shifts. |

## AUTHORS BIOGRAPHY

**Hellstrome Young Akuma** is a doctoral candidate at the Faculty of Engineering and Life Sciences, Universiti Selangor (UNISEL), Malaysia. He earned his Bachelor's degree in Aeronautical Engineering from Shenyang Aerospace University, Liaoning, China, in 2016. In 2018, he pursued a Master's degree in Engineering at UNISEL, where his research focused on the mathematical modelling and control systems of Ground Effect Vehicles. Currently, his doctoral research centres on optimizing ergonomic solutions for industrial applications by integrating advanced design tools and emerging technologies.

**Nazlin Hanie Abdullah** received a bachelor's degree in Computer Aided Design and Manufacture from Universiti of Malaya, Kuala Lumpur, Malaysia. She pursued her Master's Degree in Manufacturing Systems Engineering, Universiti Putra Malaysia, Selangor, Malaysia. Her Doctor of Philosophy is gained in PhD in Engineering Design, Universiti Malaya, Kuala Lumpur, Malaysia. Her current field placement is with Universiti Selangor in Mechanical Engineering Division, Faculty of Engineering & Life Sciences, Universiti Selangor, Malaysia for twenty two years. Her research area is ergonomics, human factor, and product design as well.