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Assessing the exposure to musculoskeletal and environmental risk factors among metal mechanical workshop operators

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Abstract
Metal mechanical workshop operators perform physically demanding and repetitive tasks that elevate the risk of work-related musculoskeletal disorders (WMSDs) while also being exposed to hazardous environmental conditions. This study assessed the prevalence of WMSDs, evaluated working postures, and examined air pollution and noise levels in small- to medium-sized metal mechanical workshops in Jeddah, Saudi Arabia. A total of 36 operators from 11 workshops participated. Data on musculoskeletal discomfort were collected using a body parts discomfort survey, and postural risks during job tasks were analyzed using the Rapid Upper Limb Assessment (RULA) method. Environmental conditions were evaluated by measuring particulate matter concentrations ($PM_{2.5}$ and PM_{10}) with an air quality monitor and workplace noise levels using a sound meter. Results showed that most operators experienced pain in the wrists and hands, lower legs, ankles and feet, thighs, neck, and lower back. RULA scores indicated poor working postures and a high risk of musculoskeletal strain. Elevated concentrations of $PM_{2.5}$ and PM_{10} were detected in most workshops, and noise levels in several sites exceeded the recommended limit of 85 dBA. These findings demonstrate that workshop operators are susceptible to substantial risks of WMSDs, respiratory problems, and noise-induced hearing loss, underscoring the need for improved environmental controls.
Keywords: *Musculoskeletal disorders, body postures, lathe, milling, ergonomics, environmental pollution, particulate matter, noise.*

I. Introduction

Steelworks are critical processes in manufacturing industries, contributing significantly to the production of various components across different sectors. However, these operations are often associated with musculoskeletal loadings, mental exhaustion, and environmental challenges, particularly air and noise pollution. To the author's knowledge, no efforts were made to assess the work-related musculoskeletal disorders (WMSDs) or environmental risk factors among metal mechanical workshop operators in Saudi Arabia.

Occupational disorders continue to rise globally, posing a significant challenge to the workforce. Musculoskeletal disorders (MSDs) affect approximately 1.71 billion individuals worldwide and account for an estimated 149 million years lived with disability [1]. Such conditions substantially reduce productivity, mainly due to increased absenteeism. In Norway, for instance, the cost of productivity loss per worker has been estimated at €343 per workday due to absenteeism and €227 per workday due to work assessment allowance and disability pension [2]. In particular, work-related musculoskeletal disorders (WMSDs) are strongly associated with biomechanical loading factors such as manual material handling, repetitive upper-limb movements, and sustained or awkward postures [3].

A study by [4] reported a Rapid Entire Body Assessment (REBA) score of five, indicating a medium level of risk for workers engaged in milling and lathe operations. This was primarily due to the mechanical loading imposed during task execution. Another study [5] found a final Rapid Upper Limb Assessment (RULA) score of 7 for the milling machine operators' left and right sides. Another study [6] reported higher REBA and RULA scores for milling and lathe operations performed by three workers, with REBA scores ranging from 4 to 14 (medium to very high risk) and RULA scores ranging from 3 to 7 (low to very high risk).

A cross-sectional survey involving 148 milling machine operators (74 hand-operated and 74 electrically operated) using the Nordic questionnaire [7] found that 77% of hand-operated and 50% of electrically operated machine operators reported WMSD symptoms, most commonly in the shoulders (85.1%) and lower back (46%). Another study [8] reported that lathe workers most frequently experienced WMSDs in the neck (71.4%), shoulders (71.4%), and waist (57.1%). A subsequent study [9] found WMSD prevalence among lathe and drilling machine operators in the lower back (65%), wrists (45%), shoulders (35%), and ankles (35%). Similarly, [10] reported a 12-month prevalence of LBP (71%), neck pain (61%), and shoulder pain (55%) among workers in a steel industry performing drilling operations.

Additionally, some working settings expose workers to poor environmental conditions, such as air pollution and noise resulting from the various industrial activities. Various works [11-14] evaluated the air pollution generated from the steel industry. A study investigated indoor air quality in steel-making locations across Saudi Arabia [11]. Their results revealed that the steel-making industry was the primary source of indoor air pollution. More specifically, Al-Zboon and Forton's results showed high concentration levels of PM_{10} and $PM_{2.5}$ in the furnace area (479 and 182 µg/m³), slag area (294 and 25 µg/m³), and the scrap area (195 and 32 µg/m³). A similar study in Cilegon, Indonesia [12] also revealed high concentration levels of $PM_{2.5}$ measured at four steel industry locations. The highest $PM_{2.5}$ levels were measured at location 3 (125.42 µg/m³), location 2 (92.05 µg/m³), and locations 1 and 4 (91.97 µg/m³). Another study [13] showed that workers who perform most of the steelworks are exposed to more than the permissible concentration limits, specified by the local Romanian authority, of breathable powder (10 mg/m³), carbon dioxide (CO_2) (9000 mg/m³), and carbon monoxide (CO) (20 mg/m³). The adverse health effects from exposure to particulate matter (PM_{10} and $PM_{2.5}$) are well-documented, and there is no evidence of a safe concentration threshold below which no adverse health effects occur [14].

A study [15] assessed the noise levels at sheet metal workshops performing cutting, drilling, and grinding activities. They demonstrated that the measured noise levels ranged between 82.3 and 110.3 dBA. Nyarubeli et al. [16] examined noise exposures in four metal factories in Tanzania. The study results revealed that the workers in the four iron and steel factories were exposed to an average noise level of 92.0 dBA without hearing protection, and thus, were at a high risk of developing noise-induced hearing loss (NIHL). A later study [17] examined the noise levels at various workshops performing machining activities. Their results revealed that noise levels surpass 100 dBA for welding operations, and exceed 85 dBA for drilling, milling, and grinding operations, which they explained would put the workers at these sites at an increased risk of NIHL. Another study [18] evaluated the noise levels during the milling of cast iron products. Their findings showed that the generated noise levels ranged between 80 and 92 dBA.

In summary, workers involved in steelwork in various parts of the world are exposed to WMSD and environmental risk factors. Assessing WMSD risk factors in the workplace and examining the air quality and noise levels at the metal mechanical workshops is critical. The current study aims to assess the lathe operators' body posture while performing the frequently performed tasks, determine the prevalence of WMSDs, evaluate the mental exhaustion, and examine the air quality and noise levels at the metal mechanical workshops in Jeddah, Saudi Arabia.

II. Methods

2.1 Approach

Quantitative and qualitative assessment methods were used to analyze the ergonomic and environmental concerns in the metal mechanical workshops in Jeddah city. The qualitative assessment methods included interviewing the workshop's operators using the body parts discomfort survey, a 2-part questionnaire. The first part involved questions about personal information, while the second part involved questions about musculoskeletal pain in the various body parts. Furthermore, RULA [19] was applied to assess the level of risk associated with performing the job tasks. The quantitative assessment included air and noise pollution measurements in the workshops visited.

2.2 Participants

The study focused on small-to-medium-sized metal mechanical workshops in Jeddah, targeting operators involved in various mechanical tasks. The inclusion criteria for participation required individuals to agree to take part in the study voluntarily. They must have worked in metal mechanical workshops for at least three months and use hand-operated machines to perform activities such as lathing, milling, drilling, cutting, welding, grinding, or sanding. Initially, fifty operators from different workshops were approached, but only thirty-six individuals from eleven workshops consented to participate voluntarily. All participants were male, representing a range of ethnicities. Before the interviews, each participant received a consent form approved by the University of Jeddah's Bioethics Committee of Scientific and Medical Research (Application #UJ-REC-151). After reviewing and signing the consent forms, the research assistants conducted one-on-one interviews using a structured two-part questionnaire.

2.3 Operators Interview

A modified body part discomfort survey was made available online to assess WMSD symptoms and potential risk factors among the operators. The survey link was preloaded onto an iPad for ease of access. Research assistants guided each participant through the questionnaire on the iPad, ensuring participants clearly understood each item.

The questionnaire was divided into two parts. The first part gathered demographic and occupational data, including the participant's age, body weight, and height (used to calculate Body Mass Index (BMI)), the number of hours worked weekly, and the total years of experience. Their knowledge of Personal Protective Equipment (PPE) and their understanding of its importance for safety was also collected.

The second part of the questionnaire focused on assessing musculoskeletal pain. Participants were asked to rate the intensity of pain on a scale from 0 (i.e., no pain) to 10 (i.e., very severe pain), and to indicate the frequency of pain in various body areas using a four-point Likert scale: never, occasionally, often, or always. The specific body areas included both sides of the neck, shoulders, elbows, upper back, lower back, forearms, hips, wrists/hands, knees, lower legs, and ankles/feet.

2.4 Rapid Upper Limb Assessment (RULA)

Assessing operators' body posture during job tasks in metal mechanical workshops is critical to understanding their exposure to potential WMSDs. To evaluate this exposure, the study employed the RULA method, a validated tool for postural assessment [20–22]. RULA was used to analyze the operators' posture while performing various tasks in the workshop, helping to identify potential risk factors associated with WMSDs. The scores derived from the posture analysis were then used to determine the overall risk level for each operator. RULA categorizes risk into four action levels, as outlined in Table 1 [19].

Table 1. RULA Scoring [19]

Score	Action Required
1-2	Acceptable posture
3-4	Further investigation, change may be required
5-6	Further investigation, change soon
7+	Investigate and change immediately

2.5 Air Quality

The air quality in the metal mechanical workshops was evaluated by measuring the concentration levels of fine particulate matter 2.5 ($PM_{2.5}$), particulate matter 10 (PM_{10}), and carbon dioxide (CO_2). A portable Temtop® (Elitech Technology, Inc., Model M2000, USA) air quality monitor was used. The monitor recorded the concentration of these pollutants every minute. The monitor was positioned in the middle of the workshop for ten minutes to assess short-term exposure. Measurements were taken from eleven different workshops. Only maximum concentrations of pollutant substances, including $PM_{2.5}$, PM_{10}, and CO_2, will be presented to highlight the significance of air quality concerns in the metal mechanical workshops.

The Air Quality Index (AQI), created by the U.S. Environmental Protection Agency (EPA) under the Clean Air Act, is a standardized, color-coded nationwide system to communicate air quality data to the public. The AQI converts pollutant concentrations into a scale ranging from 0 to 500, as shown in Table 2 [23]. Additionally, an online AQI calculator website (AirNow.gov) was utilized to calculate the AQI and obtain the AQI category (e.g., good, moderate, etc.) for $PM_{2.5}$ and PM_{10}. For the CO_2 measurements, concentration levels below 5000 ppm will be considered acceptable as per OSHA 8-Hour TWA permissible exposure limit (PEL).

Table 2. Safe concentrations for $PM_{2.5}$ and PM_{10} exposures [23]

Pollutant	Status					
	Good	**Moderate**	**Unhealthy for sensitive groups**	**Unhealthy**	**Very unhealthy**	**Hazardous**
$PM_{2.5}$ (µg/m³)	≤12	12.1-35.4	35.5-55.4	55.5-150.4	150.5-250.4	≥250.5
PM_{10} (µg/m³)	≤54	54.1-154	154.1-225	255.1-354	354.1-424	≥425

2.6 Noise Level

An essential aspect of assessing the safety concerns in metal mechanical workshops is the employees' exposure to noise, as some tasks require using equipment that produces high noise levels. A VLIKE LCD Digital Audio Decibel Meter device (VLIKE, Model VL6708, China) was utilized to measure the sound level in various locations in each workshop. The measurements lasted for 30 minutes in each workshop. Average and maximum measurements were compared with the National Institute for Occupational Safety and Health (NIOSH) recommended exposure limit (REL) of 85 dBA over an 8-hour workday. All instruments (i.e., the air quality monitor and sound meter) were calibrated before data collection according to the procedures specified by the manufacturers of both devices to ensure accurate and reliable measurements.

2.7 Apparatus

Before participating, each participant reviewed an approved institutional informed consent form, which outlined their role in the study, its purpose, and objectives. Upon agreeing to participate, they signed the consent form. Each participant's body mass was then measured (without shoes) using a digital weight scale, and their height was recorded using a stadiometer.

Air quality monitor and sound meter devices were utilized as mentioned earlier. Additionally, a smartphone was used to record video footage of the lathe shops and operators performing various tasks. The recorded videos were analyzed to capture snapshots of the operators' awkward body postures. The motion analysis software 'Kinovea, version 0.8.15,' which is available for free, was employed to measure the angles of the operators' body parts. The awkward postures were then analyzed using RULA through the cloud-based ErgoPlus© software on a Windows 10 laptop.

2.8 Statistical Analysis

The operators' responses to the survey were analyzed using Microsoft Excel to store data, perform basic statistical analyses (including descriptive statistics), and generate visual charts. The prevalence of musculoskeletal pain across various body regions was subsequently estimated. This analysis focused exclusively on respondents who answered "*Yes*" to the question: "*Have you ever had any musculoskeletal pain during the last year that you believe is related to your work?*"

IBM SPSS Statistics version 20.0 (IBM Corp., Armonk, NY, USA) software was employed to investigate associations between ordinal variables further. Variables analyzed included demographic characteristics (e.g., age and BMI), job characteristics (e.g., weekly working hours and years of experience), and work-related outcomes (such as physical exhaustion, mental exhaustion, and pain ratings for each assessed body region). Pain intensity was rated on a scale of 0 to 10, where 0 indicated no pain and 10 indicated severe pain. Other ordinal variables were classified and coded (i.e., from 1 to 4) as detailed in Table 3.

Table 3. Categories and codes for the survey variables

Variable	**Category (code)**			
Age	20-29 (1)	30-39 (2)	40-49 (3)	>49 (4)
BMI	≤23 (1)	24-28 (2)	29-33 (3)	>33 (4)
Weekly working hours	40-49 (1)	50-59 (2)	60-69 (3)	>69 (4)
Years of experience	<1 Year (1)	1–5 Years (2)	6–10 Years (3)	>10 Years (4)
Physical exhaustion	Never (1)	Occasionally (2)	Often (3)	Always (4)
Mental exhaustion	Never (1)	Occasionally (2)	Often (3)	Always (4)

Kendall's tau, a non-parametric correlation test, was conducted using the IBM SPSS software to evaluate the strength and direction of associations between these ordinal variables. Only responses from participants who reported musculoskeletal pain in the past year were included in this analysis. Additionally, the Pearson correlation coefficient test was carried out using the IBM SPSS software to measure the strength and direction of the association between the concentrations of the three air pollutants (i.e., $PM_{2.5}$, PM_{10}, and CO_2) and noise levels in the various workshops. Interpretations of the Kendall's tau and the Pearson correlation coefficients are summarized in Table 4 [24].

Table 4. Interpretation of the correlation coefficients [24]

Correlation coefficient	**Interpretation**
0.00-0.10	Negligible correlation
0.10–0.39	Weak correlation
0.40–0.69	Moderate correlation
0.70–0.89	Strong correlation
0.90–1.00	Very strong correlation

III. Results

3.1 Personal Characteristics

Interviews were conducted with 36 participants from 11 workshops located in Jeddah. Table 5 shows the participants' demographic information. About 17% of the study sample consists of participants aged between 20 and 29 years old, with the largest group being those aged between 30 and 39 at 33%. Participants aged between 40 and 49 comprised 28% of the sample; the last group was those over 49 years old, accounting for 22% of the participants. The body mass index (BMI) was calculated in Excel by dividing the participant's weight (kg) by the square of their height in (m). The average (SD) BMI in the overweight category was 27.8 (4.7) kg/m².

Table 5. Participants' demographic information

Characteristic	Mean (SD)
Age (years old)	40.1 (10.2)
Weight (kg)	81.1 (16.2)
Height (cm)	170.5 (7.7)
BMI (kg/m²)	27.8 (4.7)

Furthermore, the responses showed that most (86%) participants are right-handed, while the rest are left-handed. The results also revealed that most participants (58%) have more than nine years of experience in the metal mechanical workshop job (Figure 1).

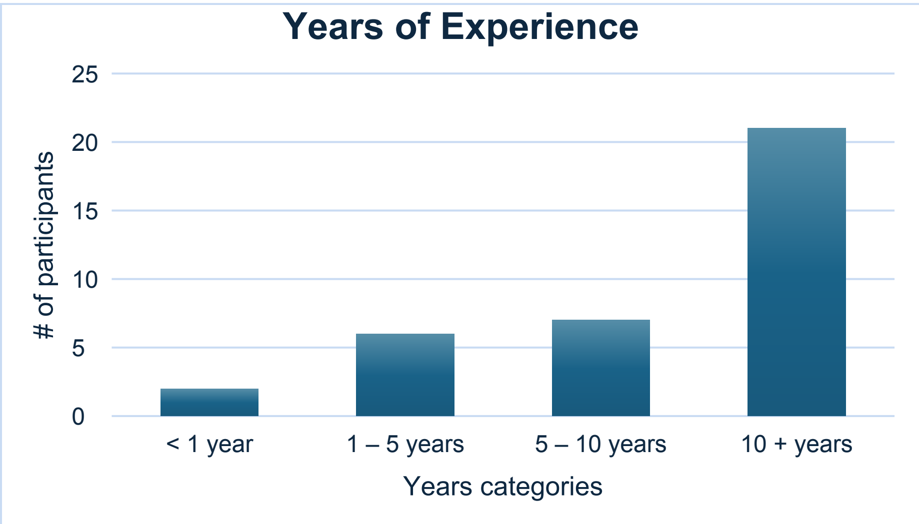


Figure 1. Participants' years of experience

Also, the results revealed that 42% of the participants are unaware of the potential injuries they may encounter while performing the job tasks. The knowledge about personal protective equipment (PPE), such as face masks and hearing protection gear, required to perform job tasks safely in metal mechanical workshops was investigated. The responses showed that 11% do not know PPE, while 83% limited PPE knowledge. Only 6% are very knowledgeable regarding PPE.

3.2 Job Characteristics

All operators stated that they get an hour break during the shift and work six days a week. Thirty-three percent of the operators work 40 to 49 hours per week, with an average of about 8 hours per day. Moreover, 11% of the operators work 50-59 hours a week, with an average of 9 hours daily. Too long working hours groups, those who worked 60 to 69 and more than 69 hours weekly, represented 36% and 19% of the total sample, for an average of about 11 and 12 hours a day, respectively. According to the responses, operators who worked more than 70 hours a week usually tend to perform more managerial tasks at the workshop. Therefore, they work longer hours than other employees.

The most frequent tasks performed at the visited metal mechanical workshops included lathing, milling, drilling, cutting, welding, grinding, and sanding. Information obtained from participant interviews and worksite observations indicated that the tasks described above involve several ergonomic risk factors. These include awkward postures (e.g., bending and reaching), repetitive movements, forceful exertions, static muscle loading, and prolonged periods of standing or sitting. Table 6 describes the physical requirements while performing the various tasks at the visited metal mechanical workshops and the potential risk factors.

Table 6. Job tasks' physical requirements

Task	Most affected parts	Key risk
Lathing	Neck/upper back, shoulders, lower back, hands, legs/feet	Awkward reach, tool handling, gripping, manipulation, prolonged standing
Milling	Neck, arms/forearms, wrists, legs/feet	Leaning, repetitive movements, manual control, prolonged standing
Drilling	Neck/upper back, forearms/wrists, hands	Awkward setup, torque, forceful pushing
Cutting	Lower back, hands	Lifting metal, repetitive torso flexion, forceful pushing
Welding	Neck/upper back, shoulders, arms	Static load, neck and torso flexion, precision strain
Grinding	Neck/upper back, lower back, shoulders, forearms, wrists/hands	Forward head posture, torso bending, static loading, forceful gripping, vibration
Sanding	Neck/upper back, lower back, wrists/hands	Awkward posture, prolonged standing, repetitive motion, forceful pushing

3.3 Exposure

3.3.1 Air Pollution

Air quality was assessed in the eleven metal mechanical workshops. Table 7 presents the maximum measurements of air pollutants, including $PM_{2.5}$ and PM_{10}, along with the calculated AQI and corresponding risk category (according to EPA standards). Additionally, Table 7 shows the maximum concentrations of the measured CO_2 and the corresponding risk category (according to NIOSH REL). Notably, workshop 9 is classified as having hazardous air quality conditions in terms of $PM_{2.5}$ (maximum concentrations ≥ 250.5 µg/m³) and PM_{10} (maximum concentrations ≥ 425 µg/m³). Additionally, Workshops 6 and 2 are classified as very unhealthy in terms of $PM_{2.5}$, very unhealthy in terms of PM_{10} in Workshop 6, and unhealthy in terms of PM_{10} for Workshop 2. The air quality results obtained for all workshops are tabulated in Table 7.

Table 7. Air pollution measurements

Workshop	**$PM_{2.5}$ (µg/m³)**			**PM_{10} (µg/m³)**			**CO_2 (PPM)**	
	Max concentration	**AQI**	**Category**	**Max concentration**	**AQI**	**Category**	**Max concentration**	**Category**
1	27	84	Moderate	43	40	Good	376.7	Acceptable
2	161	236	Very Unhealthy	259	153	Unhealthy	326.1	Acceptable
3	21	73	Moderate	32	30	Good	236.1	Acceptable
4	21	74	Moderate	32	31	Good	233.3	Acceptable
5	77	166	Unhealthy	120	83	Moderate	250.0	Acceptable
6	236	322	Very Unhealthy	388	248	Very Unhealthy	257.8	Acceptable
7	51	139	Unhealthy for sensitive groups	82	64	Moderate	253.3	Acceptable
8	62	156	Unhealthy	102	74	Moderate	387.2	Acceptable

9	314	477	Hazardous	487	370	Hazardous	248.3	Acceptable
10	75	165	Unhealthy	117	82	Moderate	503.3	Acceptable
11	22	75	Moderate	33	31	Good	318.3	Acceptable

3.3.2 Noise pollution

The noise level was also assessed in the 11 metal mechanical workshops visited. The average and maximum noise levels are shown in Table 8. Notably, both average and maximum noise levels in workshops 1, 2, 5, 7, and 11 exceed the NIOSH REL of 85 dBA. Only the maximum noise levels at workshops 4 and 6 exceed the NIOSH REL. This suggests that the operators at the workshops mentioned above are at risk of developing noise-related hearing loss, mainly since none of the operators at the 11 workshops were observed wearing any hearing protective gear.

Table 8. Noise measurements

Workshop	Average dBA	Maximum dBA
1	86.3	90
2	90.4	93.4
3	80	83.6
4	80.6	87.5
5	87.8	89.3
6	85	97.9
7	95.7	100.4
8	75	79.6
9	73.4	78.4
10	75.5	78.9
11	85.3	88.7

3.3.3 Musculoskeletal Loadings

The results showed that only 26 (72%) participants reported musculoskeletal pain in various body parts. Since, the objective was to assess the distribution of musculoskeletal pain among operators who answered "Yes" to the question of having musculoskeletal pain/discomfort during the past year, the pain prevalence in a specific body part was calculated in which the numerator was the number of participants who reported the pain in that body part, while the dominator was the total number of individuals who reported any pain in any body part (i.e., n= 26). Figure 2 shows the prevalence of musculoskeletal pain in various body parts. It can be concluded that wrists/hands had the highest prevalence (81%), followed by an equal prevalence (73%) of both lower legs and ankles/feet. Neck and thighs pain also showed an equal prevalence (69%). A lower equal pain prevalence (65%) was shown for the lower back and knees. A slightly lower prevalence (62%) was demonstrated for the shoulders and upper back. Other body parts, including elbows, forearms, and hips, showed a pain prevalence lower than 50%.

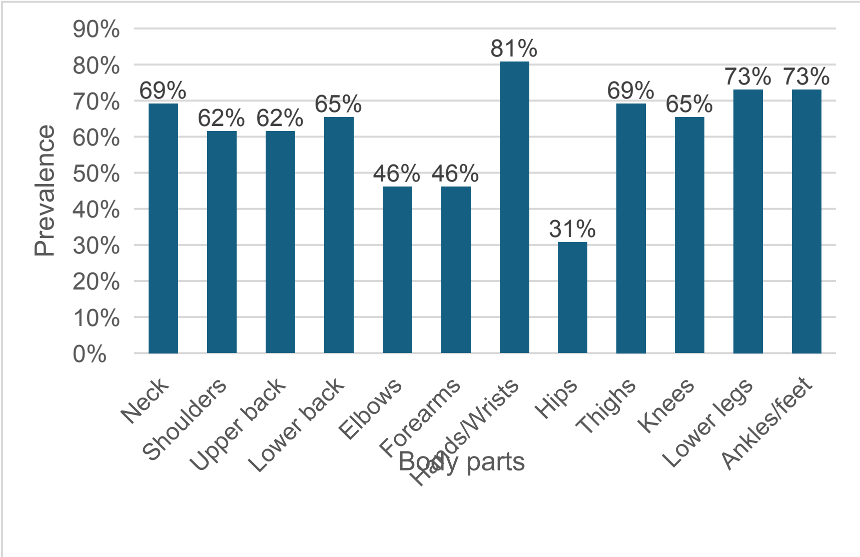


Figure 2. Body parts musculoskeletal pain prevalence

The maximum, minimum, median, and pain rating ≥ 5 for body part ratings on a scale from 0 to 10 are shown in Table 9. The minimum pain level for all body parts was 0 out of 10, indicating that various participants rated the pain in these body parts as 0. The maximum pain level, on the other hand, ranged between 8 and 10. The highest median and percentage of pain ≥ 5 was for the ankles/feet (7, 69%), lower legs (6, 65%), knees (6, 62%), wrists/hands (5, 62%), lower back (6, 58%), thighs (4, 42%), shoulders (3.5, 42%), and neck (4, 42%).

Table 9. Body parts musculoskeletal 0-10 pain ratings

Body part	Maximum	Minimum	Median	Pain rating ≥ 5
Neck	8	0	4	42%
Shoulders	10	0	3.5	42%
Upper back	9	0	4	46%
Lower back	9	0	6	58%
Elbows	8	0	0	15%
Forearms	8	0	3	27%
Wrists/Hands	10	0	5	62%
Hips	9	0	0	23%
Thighs	10	0	4	42%
Knees	10	0	6	62%
Lower legs	10	0	6	65%
Ankles/feet	10	0	7	69%

Working in the metal mechanical workshops is physically demanding. Thus, one of the survey questions was to assess the operators' physical exhaustion rating at the end of the workday. The results revealed that 19% of the operators "always" feel physically exhausted after the workday due to the nature of their tasks, including awkward postures, repetitive motion, static loading, and prolonged standing. Additionally, 28% and 33% of the participants indicated they "often" and "occasionally" feel physically exhausted, respectively, at the end of the workday. On the other hand, only 19% stated they "never" feel any physical exhaustion at the end of the workday.

3.3.4 Psychosocial Stressors

Another question in the survey addressed operators' feelings of mental exhaustion at the end of the workday. The results suggest that mental stressors have a minor impact in metal mechanical workshops compared to the physical effects of the workload. It was revealed that 14% of participants stated they "always" felt mentally exhausted, 19% reported "often", 39% indicated "occasionally", and 28% indicated they "never" experienced mental exhaustion at the end of the workday.

3.4 Correlation

The Kendall's Tau correlation test results are presented in Table 10. A moderate positive association was observed between age and years of experience ($\tau = 0.497$, $p \leq 0.01$), as well as between age and physical exhaustion ($\tau = 0.513$, $p \leq 0.05$). Additionally, age showed a weak positive association with upper back pain ($\tau = 0.355$, $p \leq 0.05$). Body Mass Index (BMI) exhibited a weak positive correlation with thigh pain ($\tau = 0.335$, $p \leq 0.05$). Years of experience were also moderately associated with physical exhaustion ($\tau = 0.414$, $p \leq 0.05$), while physical exhaustion demonstrated a weak positive relationship with lower legs pain ($\tau = 0.343$, $p \leq 0.05$).

A moderate positive association was identified between neck pain and shoulder pain ($\tau = 0.603$, $p \leq 0.01$), upper back pain ($\tau = 0.585$, $p \leq 0.01$), and elbow pain ($\tau = 0.463$, $p \leq 0.01$). Weak positive correlations were also observed between neck pain and lower back pain ($\tau = 0.345$, $p \leq 0.01$), as well as lower legs pain ($\tau = 0.370$, $p \leq 0.05$). Shoulder pain was weakly positively associated with upper back pain ($\tau = 0.353$, $p \leq 0.05$), lower back pain ($\tau = 0.359$, $p \leq 0.05$), and lower legs pain ($\tau = 0.348$, $p \leq 0.05$). Moreover, a moderate positive association was found between shoulder and elbow pain ($\tau = 0.433$, $p \leq 0.01$). A moderate positive relationship was also noted between upper back and lower legs pain ($\tau = 0.440$, $p \leq 0.01$). Elbow pain had a weak positive correlation with lower forearm pain ($\tau = 0.378$, $p \leq 0.05$), and a similar weak association was found between forearm pain and wrists/hands pain ($\tau = 0.351$, $p \leq 0.05$).

Table 10. Kendall's Tau coefficient for survey variables
**Correlation is significant at the 0.01 level (2-tailed). *Correlation is significant at the 0.05 level (2-tailed).

	Age	Weekly working hours	BMI	Years of Experience	Mental Exhaustion	Physical exhaustion	Neck pain	Shoulders pain	Upper back pain	Lower back pain	Elbows pain	Forearms pain	Wrists/ Hnads pain	Hips pain	Thighs pain	Knees pain	Lower leg pain	Ankles/ feet pain
Age	1.000																	
Weekly working hours	0	1.000																
BMI	0	-0.213	1.000															
Years of Experience	.497**	0.248	0.187	1.000														
Mental Exhaustion	0	-.342*	0.097	0.010	1.000													
Physical exhaustion	.513**	0.104	-0.272	.414*	0.263	1.000												
Neck pain	0	0.054	-0.155	0.277	0.166	0.320	1.000											
Shoulders pain	0	-0.008	-0.164	0.146	0.163	0.073	.603**	1.000										
Upper back pain	.355*	0.135	0.008	0.327	0.202	0.281	.585**	.353*	1.000									
Lower back pain	0	-0.101	-0.155	0.018	0.071	0.117	.345*	.359*	0.256	1.000								
Elbows pain	0	-0.022	-0.171	-0.030	-0.049	0.027	.463**	.433**	0.282	0.152	1.000							
Forearms pain	0	-0.045	-.370*	-0.181	-0.067	0.000	0.111	0.008	0.020	-0.004	.378*	1.000						
Wrists/Hnads pain	0	-0.113	-0.115	-0.247	0.322	0.093	0.172	0.192	0.007	0.044	0.240	.351*	1.000					
Hips pain	0	0.085	-0.203	-0.160	0.163	0.264	0.119	0.071	0.041	-0.031	0.180	0.177	.381*	1.000				
Thighs pain	0	-0.093	.335*	0.022	.344*	0.134	-0.069	-0.096	0.201	-0.098	-0.235	-0.215	0.029	0.172	1.000			
Knees pain	0	0.168	0.205	0.239	-0.037	0.154	0.034	0.162	0.134	0.093	0.030	-0.229	-0.015	0.145	0.214	1.000		
Lower leg pain	0	0.027	0.104	0.279	.386*	.343*	.370*	.348*	.440**	0.028	0.222	-0.011	.318*	-0.034	0.260	0.168	1.000	
Ankles/feet pain	0	0.008	0.125	0.156	0.137	0.120	0.241	0.120	.375*	-0.022	0.167	0.171	0.282	0.183	0.180	0.181	.379*	1.000

Pearson correlation analysis revealed significant relationships among the air pollutants studied (Table 11). The strongest association was identified between the maximum $PM_{2.5}$ and PM_{10} levels, demonstrating a very strong positive correlation coefficient of 1.00. In contrast, a weak negative correlation was found between the maximum CO_2 levels and the peak concentrations of both $PM_{2.5}$ and PM_{10}. Additionally, a moderate negative correlation was observed between the highest noise levels and the maximum CO_2 concentrations. Finally, the relationship between maximum noise levels and the peak levels of $PM_{2.5}$ and PM_{10} was negligible and negative.

Table 11. Pearson correlation coefficients for the air and noise pollution

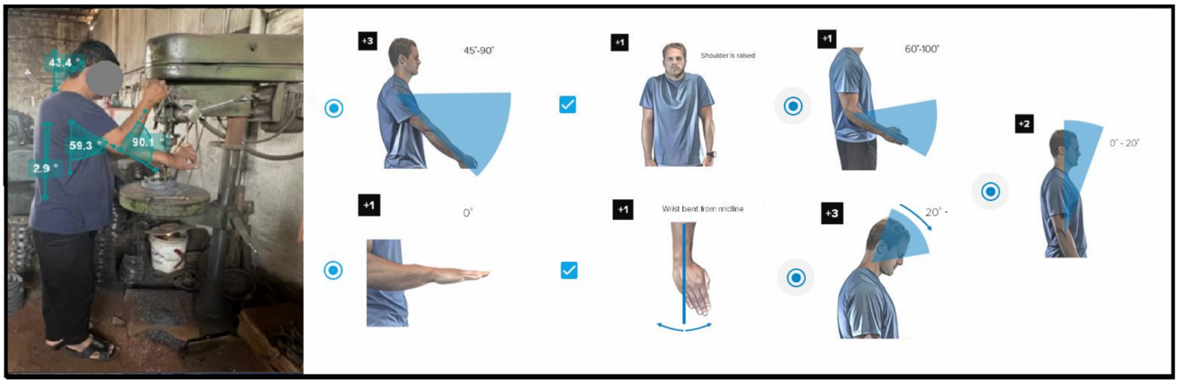
	$PM_{2.5}$	PM_{10}	CO_2	**Maximum Noise**
$PM_{2.5}$	1.00			
PM_{10}	1.00	1.00		
CO_2	-0.20	-0.20	1.00	
Maximum Noise	-0.04	-0.02	-0.40	1.00

3.5 Postural Assessment

The Rapid Upper Limb Assessment (RULA) method was employed to evaluate the postures of metal mechanical workshop operators while performing their most common tasks, including lathing, milling, drilling, cutting, welding, grinding, and sanding. The final RULA score for all assessed tasks was '7', indicating a high ergonomic risk level and the urgent need for investigation and corrective action. Figures 3 through 9 illustrate: (a) operators engaged in lathing, milling, drilling, cutting, welding, grinding, and sanding tasks, with the measurable body segment inclination angles using Kinovea software; and (b) the corresponding RULA evaluations conducted via Ergoplus software. These assessments demonstrate that operators frequently adopt awkward and potentially harmful postures during task execution.

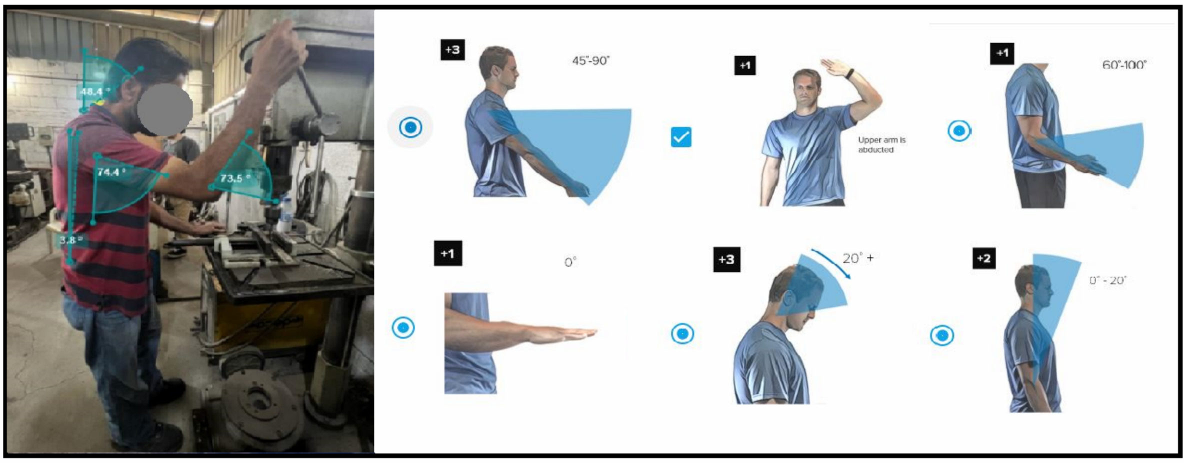
a b

Figure 3. (a) An operator performing a lathing task (b) RULA assessment - lathing task



a b

Figure 4. (a) An operator performing a milling task (b) RULA assessment - milling task



a b

Figure 5. (a) An operator performing a drilling task (b) RULA assessment - drilling task

Figure 6. (a) An operator performing a cutting task (b) RULA assessment - cutting task

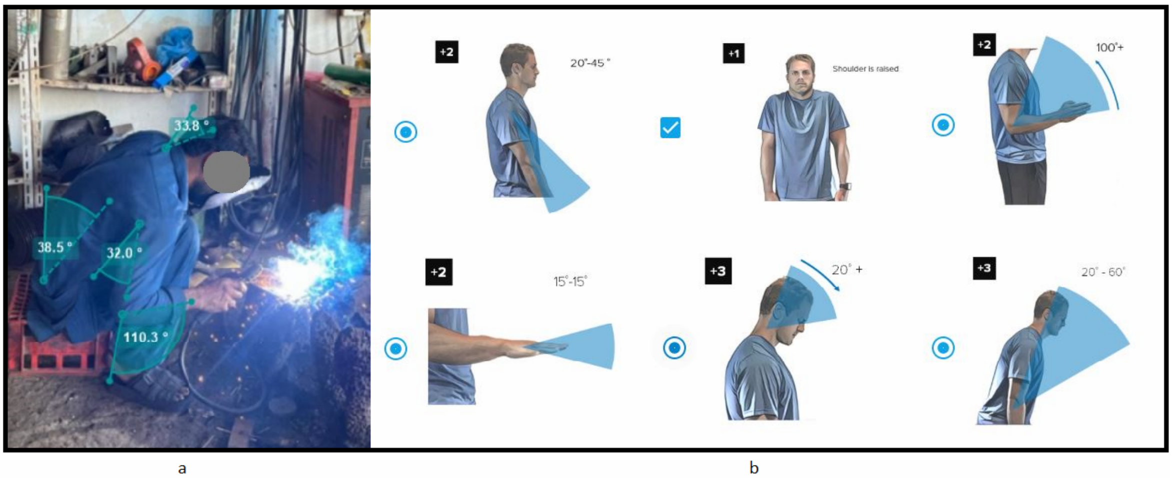


Figure 7. (a) An operator performing a welding task (b) RULA assessment - welding task

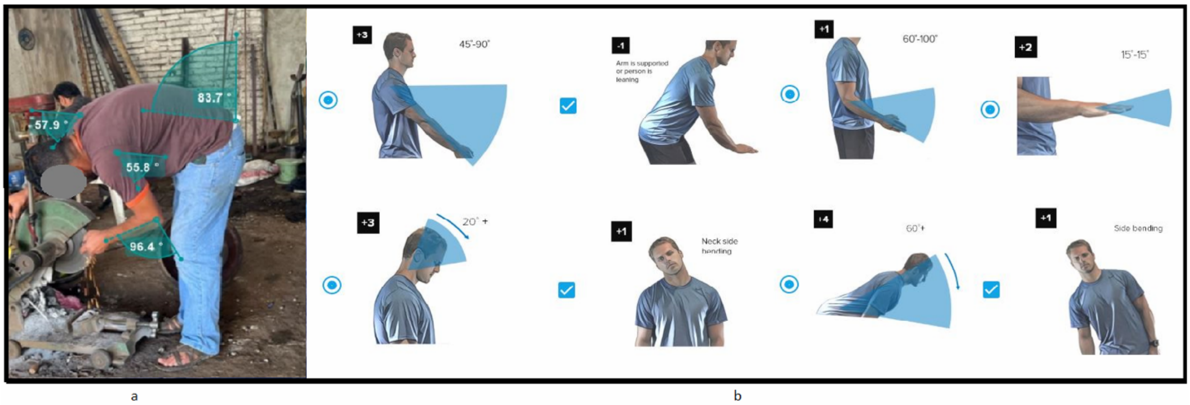


Figure 8. (a) An operator performing a grinding task (b) RULA assessment - grinding task

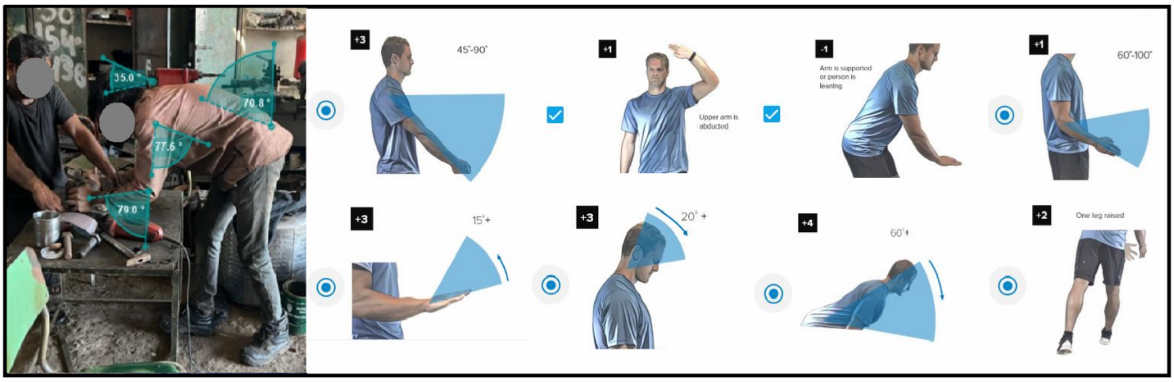


Figure 9. (a) An operator performing a sanding task (b) RULA assessment - sanding task

IV. Discussion

To the author's knowledge, this is the first study to evaluate the ergonomics and environmental hazards within the metal mechanical workshops in Jeddah, Saudi Arabia. The primary objectives were to determine the prevalence of WMSDs among the workshop operators, to assess the body postures while executing the job tasks, and the workers' mental exhaustion. Furthermore, the investigation aimed to evaluate the environmental conditions within the workshops, focusing specifically on air quality and noise levels. The findings revealed that operators in these workshops frequently adopt awkward and ergonomically unfavorable postures while performing their duties. Additionally, the analysis showed several hazardous environmental factors, including poor air quality and excessive noise levels, in multiple workshops.

4.1 Ergonomics Assessment

The RULA assessment yielded a final score of 7 for all tasks evaluated, including lathing, milling, cutting, drilling, welding, grinding, and sanding. This high score indicates a significant WMSD risk due to the adoption of awkward and ergonomically unfavorable postures during task execution, as was shown in Figures 3 through 9 above. Although all assessed tasks had the same final RULA score, indicating a high risk of WMSDs, the underlying physical demands varied significantly across tasks. During the lathing task, the worker exhibited several awkward postures, including repetitive wrist flexion and extension, wrist deviation away from the midline, trunk flexion exceeding 37°, and neck flexion greater than 40° (see Figure 3). In contrast, the cutting task involved repeated and forceful activation of the machine's lever arm, accompanied by excessive trunk and neck flexion, exceeding 55°, and an unbalanced stance (see Figure 6). Meanwhile, the grinding task was characterized by awkward arm positioning, trunk flexion beyond 80°, neck flexion over 55°, and lateral bending of both the trunk and neck (see Figure 8).

Immediate intervention and further investigation are essential to mitigate these risks and promote safer working postures. Specifically, the assessment highlighted prominent postural issues in the upper and lower arms, wrists, neck, and trunk. These findings align with those of [5], who reported a final RULA score of 7 when evaluating workers' postures while performing milling operations. Conversely, a study by [6] RULA scores ranged from 3 to 7 for workers performing hand-operated lathing and milling tasks. Workstation modifications are recommended to address these ergonomic concerns, including adjusting work surfaces to chest height, improving lighting conditions for better visibility, and refining control mechanisms to facilitate easier operation.

4.2 WMSDs

The highest prevalence of WMSDs in this study was observed in the wrists/hands, with 81% of operators affected, significantly higher than in other body parts. Wrists/hands pain rating of ≥5 was reported by 62% of the operators. This elevated risk can be attributed to several job-specific factors at the metal mechanical workshops, including forceful gripping, pushing, static loading, repetitive motions, and vibration exposure. A previous study by [9] reported a lower WMSD prevalence for the wrists (45%) than the current study's findings (81%). This discrepancy may be linked to differences in the experience levels of the participants in the two studies, particularly in their ability to perform job tasks in a safe and ergonomically sound manner. Additionally, variations in operators' awareness of the potential risks associated with their tasks could contribute to the observed differences in WMSD prevalence, particularly in the wrists. Notably, the current study revealed that 42% of operators were unaware of the potential injuries they might sustain while working in the metal mechanical workshops.

Similarly, the present study reported a higher prevalence of WMSDs in the ankles/feet (73%) compared to the prevalence of WMSDs in the ankles (35%) reported by [9]. Ankles/feet pain rating ≥ 5 was reported by 69% of the operators. Additionally, there was notable consistency in WMSD prevalence for other body regions. For instance, the prevalence of neck WMSDs in this study was 69%, closely aligning with the 71.4% reported by [8]. Neck pain rating ≥ 5 was reported by 42% of the operators. The increased risk may be linked to the neck posture adopted by operators, such as flexion or side bending, while performing tasks. These postural habits strain the neck and affect other body regions, particularly the shoulders, upper back, and lower back. This connection is further supported by the moderate Kendall's Tau positive correlation observed between neck pain and both shoulder and upper back pain, as well as a weaker positive correlation with lower back pain. Additionally, shoulder pain exhibited a weak positive correlation with both upper and lower back pain, highlighting the interconnected nature of these musculoskeletal discomforts.

Likewise, the prevalence of lower back WMSDs was identical in both the current study and [9], each reporting 65%. Lower back pain rating ≥ 5 was reported by 58% of the operators. This increased risk is justified by the physical demands placed on the lower back, including lifting heavy workpieces, repetitive and prolonged torso flexion, and extended periods of standing. Additionally, shoulder WMSDs showed similar trends, with the current study showing a prevalence of 62%, closely matching the 71.4% reported by [8] and the 85.1% reported by [7]. Shoulders pain rating ≥ 5 was reported by 42% of the operators. Finally, the findings of Weyh et al. [10] corroborate the findings of the current study, as they similarly identified that WMSDs in the lower back, neck, and shoulders were commonly reported among their participants.

The Kendall's Tau correlation test results reveal several additional significant associations that provide valuable insights into the relationships between demographic characteristics, job characteristics, and work-related effects. A moderate positive correlation was demonstrated between age and years of experience ($\tau = 0.497$) and physical exhaustion ($\tau = 0.513$). It is worth noting that the average (SD) age of the present study's population was 40.1 (10.2) years old. These findings suggest that older individuals not only have worked for long years, but are also more likely to experience higher physical exhaustion. This could be attributed to prolonged physical loadings, leading to cumulative fatigue. Furthermore, age was weakly associated with upper back pain ($\tau = 0.355$), indicating that musculoskeletal discomfort may increase with aging, although to a lesser extent than exhaustion. A moderate positive relationship was also found between years of experience and physical exhaustion ($\tau = 0.414$). This further supports the notion that long-term occupational exposure contributes to fatigue, regardless of age.

The participants' average (SD) BMI in the present study was 27.8 (4.7) kg/m^2, which falls within the overweight BMI category. The BMI showed a weak positive correlation with thighs pain ($\tau = 0.335$), which may reflect the additional strain that excess body weight places on the lower extremities. This aligns with existing literature linking higher BMI to musculoskeletal complaints in weight-bearing regions of the body [25,26].

4.3 Mental Exhaustion

The findings from this study reveal significant concerns regarding the working hours and mental health of operators exposed to polluted environments. With 36% of operators working between 60 and 69 hours per week, and an additional 19% working over 69 hours per week, it is clear that a considerable portion of the workforce is subject to long and demanding shifts. This extended work schedule can have profound implications for physical health and, as highlighted in the survey results, for mental well-being.

Thirty-nine percent of operators reported feeling occasionally mentally exhausted, 19% feeling often mentally exhausted, and 14% feeling always mentally exhausted after work. Such findings are concerning indicators of burnout and stress. Mental exhaustion can lead to a range of adverse outcomes, including decreased job satisfaction [27], lower productivity [28], and increased risk of WMSDs [29], all of which could potentially impact both worker safety and the overall effectiveness of operations, especially in polluted environments.

4.4 Air Pollution

The Pearson correlation analysis revealed a very strong positive correlation between $PM_{2.5}$ and PM_{10} concentrations, indicating that both particulate fractions vary simultaneously. This suggests they originate from common sources, such as welding and cutting operations, and may serve as closely related indicators of particulate emissions in metal workshops. Classifying workshops based on $PM_{2.5}$ and PM_{10} levels demonstrates a clear dose–response relationship between exposure and potential health risks. For $PM_{2.5}$, Workshop 9, categorized as "hazardous," represents an extremely high-risk environment. Evidence shows that $PM_{2.5}$ exposure at hazardous levels can cause acute respiratory inflammation, impaired lung function, and cardiovascular complications even in healthy individuals, with sensitive groups facing excessively higher risks [17, 30]. Additionally, Workshops 2 and 6, classified as "very unhealthy," are also of concern, as the exposures in this range have been associated with increased hospital admissions for asthma, chronic obstructive pulmonary disease, and ischemic heart disease [31]. Furthermore, the "unhealthy" environmental conditions at workshops

(5, 8, and 10) suggest that while adverse effects are more pronounced in vulnerable individuals, prolonged exposure may contribute to declines in lung capacity and elevated risk of occupational-related respiratory illness across the workforce [32,33]. Workshop 7, categorized as "unhealthy for sensitive groups," suggests that individuals with pre-existing respiratory or cardiovascular conditions are particularly vulnerable. At the same time, healthy workers may experience symptoms if exposure is sustained. Notably, even "moderate" $PM_{2.5}$ exposure levels are not risk-free. Recent meta-analyses have demonstrated that long-term exposure below guideline thresholds continues to contribute to the development of chronic respiratory and cardiovascular diseases, indicating the absence of a safe threshold [34,35].

This gradient of health risks across exposure categories illustrates a dose–response relationship, where increasing $PM_{2.5}$ concentrations are associated with progressively greater risks of musculoskeletal strain, reduced productivity, and long-term health impairment. Compared to previous studies, the $PM_{2.5}$ levels reported here slightly exceed those by [11] and [12]. A study [11] recorded levels from 25 µg/m³ ''moderate" to 182 µg/m³ "very unhealthy", while [12] reported a narrower range from 91.97 µg/m³ to 182 µg/m³, representing the "unhealthy" category.

A similar dose–response gradient is evident for PM_{10}, which in this study ranged from 32 µg/m³ (good) to 487 µg/m³ (i.e., hazardous). Workshop 9, again classified as "hazardous," denotes that adverse health outcomes are expected across all exposed workers at this workshop. High PM_{10} concentrations are strongly linked to increased respiratory symptoms, airway inflammation, and elevated risks of acute lower respiratory infections [36]. Moreover, Workshops 6 and 2, classified as "very unhealthy" and "unhealthy," respectively, also raise concern, as exposure in these categories is associated with a higher incidence of chronic bronchitis, aggravated asthma, and increased absenteeism due to respiratory illness.

Workshops with air quality in the "good" to "moderate" ranges represent relatively lower risks; however, the cumulative effects of long-term exposure, even at moderate PM levels, have been associated with accelerated lung aging, asthma, pneumonia, and hospital admissions for respiratory diseases [37]. It is worth noting that the PM_{10} levels reported in a previous study [11] slightly exceeded those in the present study, with values ranging from 195 µg/m³ "unhealthy for sensitive groups" to 479 µg/m³ "hazardous". CO levels measured in this study remained within acceptable limits according to OSHA's 8-hour TWA PEL and were significantly lower than those reported in [13].

Despite these findings, none of the operators were observed using respiratory protection, such as masks or reusable respirators. They were not wearing goggles or face shields to guard against airborne particles or flying debris. The sole exception was a welding operator who used a hand-held face shield, offering limited protection.

The owners of all workshops, especially those with air quality ranging from unhealthy to hazardous, must employ urgent interventions to safeguard operators' health and comply with occupational safety standards. These interventions may include installing adequate ventilation systems, dust vacuum extraction units, and high-efficiency particulate air filters. More importantly, implementing operator training programs focused on hazard awareness and safe work practices. Additionally, the provision and mandatory use of PPEs, such as N95 or P100 respirators and goggles or face shields, are critical for operators' safety and health. Finally, reducing the exposure time, either through minimizing the shift time or incorporating more short and frequent breaks, would also mitigate the adverse effects of pollution exposure.

4.5 Noise Pollution

The average and maximum noise level ranges observed in the current study were 73.4–95.7 dBA and 78.4–100.4 dBA, respectively. These findings are consistent with noise levels reported in previous studies [15–18]. Notably, none of the operators in the assessed workshops were observed using any form of hearing protection. This indicates that operators are regularly exposed to potentially harmful noise levels and are therefore at significant risk of noise-induced hearing loss (NIHL). Similar to air pollution, prolonged exposure to high noise levels may also contribute to mental exhaustion. Therefore, reducing the noise exposure duration could protect the operators against the NIHL and mental exhaustion. Also, the provision of, and strict adherence to, hearing protection equipment, such as earmuffs or noise-canceling headphones, is essential to safeguard operators against hearing damage and associated health risks.

4.6 Limitations

The current findings must be reviewed in light of the following limitations. First, the study included only 36 participants, which constitutes a limitation that may impact the generalizability of the results. A larger sample size could have provided more robust data and yielded different outcomes. The limited participation may have been influenced by operators' reluctance to disclose discomfort or pain experienced during their tasks and their unwillingness to be observed and evaluated. Despite the research assistants' efforts to clearly communicate the study's objectives and assure participants that their identity information would remain confidential, these factors likely contributed to the smaller sample size. Consequently, the findings should be interpreted cautiously, as the results may not fully reflect the broader population of operators.

Second, the air quality monitor was placed in the center of the workshop, and the data collection lasted 10 minutes. Positioning the monitor closer to specific operations and extending the monitoring duration could have led to different air quality readings. The extended monitoring was not feasible due to operational constraints or limited access to the visited workshop. Additionally, it is recognized that measurements from both the air quality monitor and sound meter may have been influenced by certain sources of measurement uncertainty, such as fluctuations in environmental conditions (e.g., temperature, humidity) and device-specific tolerances. However, research assistants followed the manufacturer's guidelines to minimize these uncertainties, performing regular instrument checks and recalibrating the devices between data collection sessions. Finally, the RULA assessment was conducted on only one side of the operators' bodies (i.e., right or left). Assessing both sides may have resulted in different RULA scores.

4.7 Recommendations

Based on the present study's findings, several recommendations are suggested to help protect the operators against the occupational hazards at the metal mechanical workshops as described below.

1- Work surfaces must be adjusted to be as close to chest height as possible to minimize excessive torso and neck flexion.
2- Lighting conditions need to be enhanced in the workplace to improve visibility and help reduce awkward postures of the torso and neck.
3- Machine control mechanisms need to be refined to facilitate easier operation, and thus, operations become less physically demanding.
4- Ventilation systems, dust vacuum extraction units, and high-efficiency particulate air filters must be installed to purify the air and eliminate the toxic substances.
5- Respiratory PPEs, such as N95 or P100 respirators, must be provided to protect operators from pollutant substances and fine particles.
6- Goggles or face shields must be provided to protect the operators from debris, chemical splashes, and sparks.
7- Limiting the duration of exposure to hazardous conditions, either through minimizing the shift time or incorporating more short, frequent breaks to minimize the health impacts associated with prolonged exposure, thus reducing mental exhaustion.
8- Properly enforcing appropriate hearing protection equipment, such as earmuffs or noise-canceling headphones, is essential to safeguard operators against hearing damage and other related health risks.
9- Safety training programs focusing on hazard awareness, safe work practices, and the correct use of protective equipment should be implemented regularly.

V. Conclusion

It can be concluded from the findings of the present study that the metal mechanical workshop operators are at increased risk of WMSDs due to the nature of the job tasks that require forceful wrists/hands exertions, prolonged standing, frequent torso and neck flexion, among others. Body parts with the highest pain prevalence were wrists/hands, lower legs, ankles/feet, thighs, neck, and lower back. A RULA score of 7 was obtained for all assessed tasks, which indicates that changes need to be implemented immediately to minimize the risk of WMSDs. The findings also showed hazardous and very unhealthy air quality conditions due to the increased levels of $PM_{2.5}$ and PM_{10}. Noise levels at various sites were above the NIOSH REL, which suggests that metal mechanical workshop operators are at an increased risk of developing NIHL.

Work surfaces should be positioned at chest height to enhance operator safety and comfort and minimize frequent and unnecessary neck and torso flexion. Optimizing lighting conditions is also essential to improve visibility at the work point, thereby reducing the likelihood of awkward neck postures. Furthermore, machine controls should be ergonomically designed to facilitate easier operation and reduce physical exertion. Adequate ventilation, along with the provision of appropriate respiratory and hearing protection, is critical for minimizing exposure to hazardous substances and mitigating health risks. Lastly, short and frequent breaks can significantly reduce prolonged exposure to physical and environmental stressors while reducing mental exhaustion.

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