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Ergonomic Risk Factors and Mitigation Strategies in a Semiconductor Manufacturing Company: A Case Study

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ABSTRACT

Workplace ergonomics aims to optimize workstation designs and tools to enhance safety, efficiency, and productivity while minimizing the risk of injuries. In industries like semiconductor manufacturing, repetitive tasks have been identified as key contributors to musculoskeletal disorders (MSDs), leading to conditions such as back pain, neck strain, and repetitive strain injuries. This study investigates ergonomic risks in the wafer patterning process using an Initial Ergonomic Risk Assessment (ERA) and Advanced ERA tools. The Nordic Musculoskeletal Questionnaire (NMQ) was used to collect data, revealing that workers reported discomfort in areas such as the neck, upper and lower back, wrists, thighs, and legs. The Initial ERA identified wafer patterning as the highest risk task. Advanced ERA findings, with REBA scores of 9 and 10, and ART scores indicating moderate to severe risks (13 and 12 for the left arm, 26 and 25 for the right arm), confirmed the significant ergonomic challenges in this process. A root cause analysis using the fishbone diagram further supported these findings. To mitigate these risks, the study recommends engineering controls, such as improving workstation designs and tools, alongside administrative controls, including posture training, exercise programs, and task rotation. These suggestions aim to reduce exposure to WMSD risk factors and enhance worker well-being. Ultimately, these measures will contribute to a safer and more efficient workplace for employees engaged in wafer patterning, enhancing both productivity and worker health in the long term.

Keywords: Workplace Ergonomics, Musculoskeletal Disorders (Msds), Ergonomic Risk Assessment (ERA), Semiconductor Manufacturing

1. INTRODUCTION

Ergonomics is a discipline concerned with optimising the interaction between people and the systems in which they work, with the dual aim of improving human well-being and overall system performance [1]. By tailoring workplaces, tools, and tasks to match workers' physical and cognitive capabilities, ergonomic interventions seek to reduce the risk of injury, minimise fatigue, and enhance productivity, particularly in labour-intensive and repetitive environments [2,3]. In highly technical sectors such as semiconductor manufacturing, where precision, consistency, and sustained attentional demands are critical, ergonomics is not merely a supportive consideration but a fundamental component of safe and efficient operations.

The semiconductor industry underpins modern electronics and digital technologies, supplying essential components for automotive systems, industrial automation, consumer electronics, and communication devices [4]. Across the manufacturing chain—from wafer fabrication to lithography, inspection, and packaging—operators frequently perform repetitive, fine-motor tasks in controlled cleanroom environments for prolonged periods. These tasks are often carried out in constrained spaces and under strict process requirements, increasing the likelihood of awkward postures, static loading, and repetitive motions. When ergonomic risks are not

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adequately managed, workers may experience discomfort and musculoskeletal strain, which in turn can compromise both product quality and throughput.

Musculoskeletal disorders (MSDs) represent one of the most common occupational health problems in manufacturing environments, including semiconductor facilities [5]. Cleanroom personnel are particularly vulnerable to neck, back, shoulder, and upper-limb disorders due to prolonged standing, static postures, repetitive hand use, and limited opportunities for movement [5–7]. MSDs contribute to lost workdays, increased absenteeism, reduced productivity, and higher healthcare costs [6]. The National Safety Council has reported that nearly one million MSD cases were recorded in 2021–2022, with a substantial proportion affecting the upper body, including the trunk and neck [7]. In a precision-driven sector such as semiconductor manufacturing, even moderate discomfort can reduce concentration, slow task performance, and elevate the risk of operational errors.

In Malaysia, work-related musculoskeletal disorders (WMSDs) rank among the most prevalent occupational illnesses, accounting for a sizeable proportion of reported work-related health problems across different industries [8]. Epidemiological studies have shown high MSD prevalence among Malaysian industrial workers, particularly in tasks involving manual handling, repetitive movements, and awkward postures. For example, a study in a printing manufacturing company reported that 61% of production workers experienced musculoskeletal symptoms within the past year, most frequently in the lumbar region, knees, and neck [9]. MSDs often begin as mild discomfort in the upper limbs and progressively affect the upper and lower back, neck, shoulders, and lower extremities if risk factors are not mitigated [10]. This progression underscores the need for early identification and targeted ergonomic interventions, especially in sectors characterised by repetitive and static work.

Within semiconductor manufacturing, wafer patterning is a critical process step that combines prolonged standing, visual inspection, and repetitive manual operations. Observations at a wafer patterning workstation in a semiconductor plant in Kedah, Malaysia (hereafter referred to as Company X) revealed several ergonomic concerns. Operators are required to stand continuously while manually setting wafer lots where each containing 25 wafers, and monitoring the patterning process over a cycle that can last approximately three hours. During this period, workers must oversee pattern alignment, adjust photolithography parameters, and perform quality checks while remaining in a largely static standing position. The required standing duration exceeds the two-hour limit recommended by the Department of Occupational Safety and Health (DOSH) for prolonged standing, and static neck flexion/extension beyond two hours per day similarly surpasses recommended limits [11]. To monitor the display screens, workers often maintain a static, extended neck posture, which can impose excessive load on the cervical spine and surrounding musculature, increasing the risk of neck-related MSDs [12].

In addition to prolonged standing and awkward neck posture, the wafer patterning process involves repetitive upper-limb movements, including tapping, swiping, and sustained gripping gestures. These fine, repetitive actions, performed with minimal rest breaks, heighten the risk of repetitive strain injuries (RSIs) such as carpal tunnel syndrome, tendinitis, and trigger finger [13]. DOSH guidelines indicate that performing highly repetitive tasks for more than three hours per day exceeds the recommended exposure limits [11]. When repetitive motion is combined with static postures and extended task duration, cumulative loading on muscles, tendons, and joints can lead to inflammation, chronic discomfort, and long-term functional impairment [13,14]. Over time, these factors contribute to fatigue, reduced endurance, and diminished work capacity, with implications for both worker health and process reliability.

Despite the central role of wafer patterning in semiconductor production, there is limited empirical research focusing specifically on the ergonomic risks associated with this workstation. Existing ergonomics studies in semiconductor environments often address broad manufacturing

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operations or general cleanroom conditions, leaving a gap in detailed assessments of high-risk processes such as wafer patterning. This gap is particularly relevant for Malaysian semiconductor facilities, where context-specific data are needed to guide targeted interventions that align with local regulations and workforce characteristics.

In response to these challenges, this study investigates ergonomic risk factors at a wafer patterning workstation in Company X. The research focuses on a high-risk workstation identified through the Nordic Musculoskeletal Questionnaire (NMQ) and involves two female operators under the age of 40, each with more than one year of experience at the workstation. Initial Ergonomics Risk Assessment is employed to screen for key risk factors, followed by appropriate Advanced Ergonomics Risk Assessment tools to quantify postural and task-related risks. The specific objectives of the study are: (i) to identify ergonomic risk factors experienced by workers using an Initial Ergonomics Risk Assessment approach; (ii) to assess the ergonomic risk levels using suitable Advanced Ergonomics Risk Assessment methods; and (iii) to propose feasible improvements or intervention strategies to reduce ergonomic risks at the wafer patterning workstation.

The scope of the research is confined to the wafer patterning process at Company X, with a focus on physical risk factors such as posture, repetitive motion, and static loading. The assessments are primarily based on observed task demands and worker–task interactions rather than individual psychosocial characteristics or broader organisational factors. Furthermore, the implementation of engineering controls, such as complete workstation redesign or acquisition of new equipment, is constrained by financial and operational limitations. As a result, the study emphasises practical, low-cost recommendations aimed at risk reduction rather than full-scale redesign. While these constraints may limit the extent of intervention, they reflect realistic conditions in many industrial settings and highlight the importance of incremental ergonomic improvements.

By concentrating on a critical yet under-explored process within semiconductor manufacturing, this study seeks to enrich the current understanding of ergonomic risks in wafer patterning and to provide evidence-based recommendations that support safer, more sustainable working conditions. The findings are expected to contribute to both the scientific literature on occupational ergonomics and the practical management of WMSD risks in high-precision manufacturing environments.

2. LITERATURE REVIEW

The semiconductor manufacturing industry is central to modern technology, supplying key components for electronics, automotive systems, renewable energy solutions, and advanced digital infrastructures such as artificial intelligence and 5G networks. Its core processes—including lithography, etching, doping, and deposition—demand extremely high precision and consistency, while being carried out in cleanroom environments where strict contamination control and process stability are required [15]. In Malaysia, the sector continues to grow but still faces challenges in fully adopting advanced automation due to high capital costs, maintenance requirements, and the need for specialized technical expertise. At the same time, manufacturers must cope with rapidly evolving global standards, cybersecurity concerns, and the need to upskill workers to operate increasingly sophisticated systems [16,17]. As a result, manual and semi-automated tasks remain common in many production stages, leaving workers exposed to a range of ergonomic risk factors.

Within this context, work-related musculoskeletal disorders (WMSDs) are a major occupational health concern. Tasks involving repetitive operations, awkward body postures, and prolonged static standing or sitting are strongly associated with WMSDs. A study in the electronics manufacturing sector reported a 12-month WMSD prevalence of 40.6%, with the neck (26.8%),

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shoulder (22.8%), upper back (14.9%) and lower back (14.8%) being the most frequently affected regions [16]. Contributing factors included awkward postures, lifting and carrying loads, excessive repetition, prolonged standing, and exposure to cold or fluctuating temperatures [16,17]. These findings are consistent with broader ergonomic literature, which identifies physical workload, environmental conditions, and organisational factors as key determinants of musculoskeletal outcomes [30–35]. Ergonomic interventions such as workstation redesign, provision of assistive devices, and regular rest breaks have been shown to reduce these risks and support safer, more sustainable work performance [16,17].

The wafer preparation process illustrates how these risk factors arise in semiconductor manufacturing. This process typically covers loading wafer lots into carriers, transporting them between tools, performing wafer patterning via photolithography, and inspecting patterned wafers for defects. Each lot commonly contains 25 wafers, and operators must handle them carefully to avoid contamination or damage, as defects at this stage can lead to substantial yield loss [18]. Manual material handling (MMH) during loading and carrying lots is recognised as a contributor to low back pain (LBP) and MSDs, particularly when lifting or carrying is frequent or performed with poor technique [19]. However, when basic ergonomic practices and appropriate equipment are in place, some studies report lower MSD prevalence from carrying tasks compared to highly repetitive fine-motor tasks or prolonged static postures [20].

By contrast, wafer patterning is particularly demanding ergonomically. Operators may stand continuously for three to four hours while setting process parameters, monitoring equipment status, and performing in-line quality checks. These tasks require high visual concentration and precise manual control, often encouraging static neck extension to view elevated monitors and sustained upper-limb positions to operate keyboards, mice, or touchscreens. Such postures can overload the cervical spine and shoulder musculature and are associated with conditions such as tension neck syndrome [21–23]. At the same time, repetitive tapping, swiping, and gripping movements increase the risk of repetitive strain injuries (RSIs) such as tendinitis or carpal tunnel syndrome [13,15]. DOSH guidelines indicate that standing for more than two hours and performing repetitive tasks for more than three hours per day exceed recommended exposure limits [11,14], suggesting that wafer patterning operators may be at elevated risk when these thresholds are routinely surpassed.

Inspection tasks following wafer patterning, typically conducted at microscope workstations, introduce additional ergonomic concerns. While seated work reduces lower-limb fatigue, operators frequently adopt forward-leaning postures with sustained neck flexion to view microscope fields, which can provoke discomfort in the neck, shoulders, and lower back over time. Studies have reported links between prolonged microscope use and MSDs, although symptoms are often moderate rather than extreme [25]. In combination, the wafer loading, patterning, and inspection stages expose workers to a mixture of static standing, awkward neck and trunk postures, repetitive hand movements, and visual strain that cumulatively increase WMSD risk [21–23].

Ergonomics provides a conceptual framework for understanding and managing these risks. Originating from the Greek words ergon (work) and nomos (law), ergonomics is defined as the scientific discipline concerned with human interaction with other system components, and the application of theories, principles, data, and methods to optimise human well-being and system performance [26,27]. Rather than requiring workers to adapt to poorly designed tasks, ergonomics seeks to adapt work to human capabilities and limitations. Key ergonomic risk factors include awkward postures, forceful exertions, static or sustained postures, repetitive movement, contact stress, and environmental loads such as vibration or temperature extremes [30–35]. These factors can act alone or in combination and often lead to cumulative trauma affecting muscles, tendons, ligaments, joints, and nerves [33–35]. In industrial settings such as

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semiconductor manufacturing, they manifest as lower back pain, tension neck syndrome, carpal tunnel syndrome, and related disorders [37–39].

To address these issues systematically, ergonomics risk assessment (ERA) methods are widely used. ERA provides a structured process for identifying risk factors, evaluating their severity, and prioritising interventions to prevent MSDs [40,41]. Initial ERA typically employs simple, worker-centred tools such as the Nordic Musculoskeletal Questionnaire (NMQ), which records the presence, frequency, and impact of musculoskeletal symptoms in different body regions and is widely used in occupational health research [42,43]. Other symptom-based tools such as the Cornell Musculoskeletal Discomfort Questionnaire (CMDQ) and the Body Symptom Survey (BOSS) offer additional detail on severity and frequency and have been applied to identify high-risk body areas and evaluate the effectiveness of interventions [44–46].

Advanced ERA methods provide more detailed, task- or posture-specific assessment. The Rapid Entire Body Assessment (REBA) evaluates whole-body postures, including neck, trunk, legs, and upper limbs, while incorporating force, load handling, and static or dynamic task characteristics to generate an overall risk score and recommended action level [47–49]. REBA is particularly suitable for tasks involving prolonged standing and full-body postures, such as those seen at wafer patterning workstations. The Assessment of Repetitive Tasks (ART) focuses on upper-limb intensive work, quantifying repetition rate, force, awkward wrist and hand postures, and modifying factors such as duration and recovery time [49]. Its traffic-light exposure categories help identify tasks where repetitive motion presents a medium or high risk of MSDs, making it well suited for analysing repetitive hand and wrist activity during wafer handling and parameter setting.

Evidence from multiple industries shows that combining tools such as NMQ, REBA, ART, RULA, and QEC enables comprehensive evaluation of ergonomic risks and supports targeted interventions. Studies consistently report that awkward postures, prolonged standing, and repetitive upper-limb movements are major contributors to WMSDs, and that engineering and administrative controls—such as workstation redesign, mechanical aids, improved seating and standing support, task rotation, and training—can significantly reduce risk scores and discomfort while maintaining or improving productivity [53,54].

3. METHODOLOGY

A clear overview of the sequential steps applied in this study is illustrated in Figure 1, which presents the project methodology flowchart outlining the identification, assessment, and improvement phases of the ergonomic evaluation process. This study adopted a structured ergonomic assessment methodology designed to identify, evaluate, and mitigate musculoskeletal risks associated with the wafer preparation process in semiconductor manufacturing. The methodological approach was informed by established ergonomic assessment frameworks and aligned with recognised occupational health guidelines to ensure systematic data collection, reliable risk evaluation, and evidence-based intervention planning. The overall methodology followed three sequential phases—identification, assessment, and improvement—each contributing to a comprehensive evaluation of ergonomic risks within the wafer patterning workstation.

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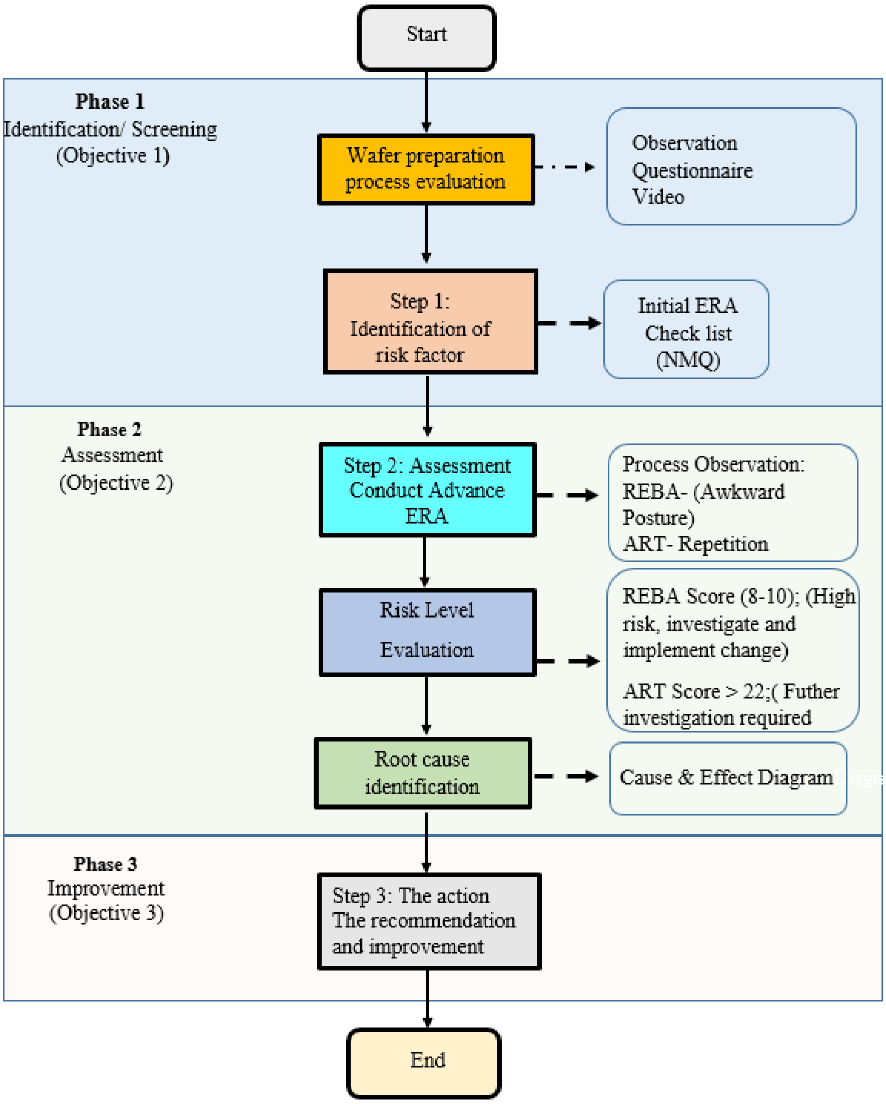

Figure 1: Project Methodology Flowchart

The identification phase focused on recognising work tasks and postures that may contribute to musculoskeletal disorders (MSDs). Direct workplace observations were first conducted to document actual worker movements, postures, task sequences, work duration, and equipment interaction. This allowed for contextual understanding of the real working conditions rather than relying solely on procedural descriptions. To complement observational data, the Nordic Musculoskeletal Questionnaire (NMQ) was administered to two experienced operators at the workstation. As a validated self-report tool, the NMQ enabled workers to identify body regions experiencing discomfort or pain over the past 12 months, helping to prioritise tasks and postures with the highest ergonomic concern. Additionally, a structured Ergonomic Risk Assessment (ERA) checklist was used to document specific risk elements such as repetitive actions, static or awkward postures, and manual handling requirements.

The assessment phase employed advanced ergonomic assessment tools to quantify risk levels and determine the severity of identified hazards. Two tools were selected due to the nature of tasks performed: the Rapid Entire Body Assessment (REBA) for postural risk evaluation and the Assessment of Repetitive Tasks (ART) for repetitive hand and wrist movements. REBA was particularly relevant because wafer patterning requires prolonged standing, neck extension, and elevated arm postures, all of which are recognised contributors to MSDs. The REBA scoring process involved analysing neck, trunk, leg, and upper limb positions, incorporating additional

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factors such as load handling and static postures. In parallel, the ART tool assessed repetition frequency, force exertion, wrist and hand posture, and adequacy of rest periods. Its traffic-light scoring system enabled clear categorisation of exposure levels, highlighting tasks that required immediate corrective action. Both REBA and ART analyses were supported by still photographs and video recordings to ensure accurate and repeatable scoring.

To further interpret assessment findings, a root cause analysis using a fishbone (Ishikawa) diagram was conducted, examining contributing factors across categories such as workstation design, tool layout, worker technique, environmental constraints, and task organisation. This analysis helped distinguish between surface symptoms and deeper systemic contributors to ergonomic risk, providing a foundation for effective intervention planning.

The final improvement phase focused on translating assessment findings into practical ergonomic solutions. Interventions were grouped into engineering controls, which involved modifying the physical work environment (e.g., workstation height adjustment, improved monitor placement, or use of supportive devices), and administrative controls, which addressed task organisation and worker behaviour. Recommendations included posture-awareness training, promoting micro-breaks, task rotation, stretching routines, and improved standard operating procedures to reduce cumulative strain. These interventions were developed to be feasible within typical industrial constraints while targeting the most critical risk factors identified during assessment.

4. RESULTS AND DISCUSSION

4.1 Observation

The wafer preparation process starts with loading the lot, operator bringing the lot to next workstation, wafer patterning process and inspection process. Table 1 shows the overall process of wafer preparation. The ergonomics assessments were carried out to validate that ergonomics problem existed in wafer patterning process.

Table 1 Process in wafer preparation

No	Process	Description
1	Load the lot	Operator is waiting for the lot to out from the stocker. The mass of the lot is 4.0 kg. The height of the rack is 1.80m.
2	Carry the lot	The operator carries a lot of 25 wafers from the stocker to the Lithography room. During a shift, the operator completes this task three times, carrying the lot to and from the Lithography room each time. The distance 10 meters. As a result, the frequency of the task is 3 tasks per shift.
3	Wafer Patterning	Operator arrived the Lithography area and load in the lot into the Litho tool. Operator manually needs to set the lot to do wafer patterning for all 25 wafers. The duration to complete for each lot takes about 3 hours.
4	Wafer Inspection	After completion of wafer patterning and etching known as removal of oxide layer, operator manually doing wafer inspection from the microscope to observe on any defect density from the microscope to check on any particles. Operator can randomly pick any five wafers to check on the defect from each lot. This process will take about 30 minutes.

4.2 Worker Demographics and Work Organization

Based on the demographic data collected from two workers, as detailed in Table 2, both individuals were assigned to the tasks accordingly. The socio-demographic section provides

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insights into participants' gender, age, work experience, tasks performed, and instances of missed workdays due to pain. According to Table 2, the age distribution of respondents indicates that both workers were below the age of 40, representing 100% of the workforce. Age is a significant factor in the development of musculoskeletal disorders (MSDs). The natural wear and tear on muscles and joints, compounded by repetitive tasks, increases susceptibility to pain and injury as individuals age. Research demonstrates that workers aged 45 to 64 have an incidence rate of MSDs over 30 cases per 10,000 full-time workers, comprising 44% of all private sector MSD cases. Workers aged 65 and over had an incidence rate of 21.2 in 2018 [55].

Table 2: Socio-demographic data

No	Variable	Classification	Frequency	Percentage (%)
A1	Work task	Load the lot	2	100%
		Carry lot	2	100%
		Wafer patterning	2	100%
		Inspection	2	100%
A2	Age	40 years below	2	100%
		40 years above	0	0
A3	Service period at industry	Below 1 year	0	0
		1 years and above	2	100%
A4	Gender	Male	0	0
		Female	2	100%
A5	Missed work days by workers due to physical pain	≤ 1	0	0
		≥ 1	2	100%

Furthermore, the prevalence of MSDs is reported to rise with age. For instance, a study found that the average age of employees with work-related musculoskeletal disorders was 40.1 years, indicating a higher prevalence among older workers [56]. However, it is critical to note that ergonomic risks are not confined to older workers. Younger workers can also face significant risks if their work environment is not ergonomically optimized. Therefore, implementing strategies to reduce ergonomic risks should remain a priority for all age groups. Gender distribution analysis revealed that 100% of the workforce at this workstation identified as female. This reflects a gender-specific workforce in this context and emphasizes the need to tailor ergonomic interventions to address health and safety concerns unique to female workers. Studies have shown that women are more susceptible to certain ergonomic hazards due to these differences [57]. Workers reported having more than one year of experience with the company, indicating workforce stability, which may result from a positive work environment or job satisfaction. Despite this retention, 100% of the workers reported missing workdays due to pain within the past year. Chronic pain, often linked to MSDs, remains one of the leading causes of work absenteeism [58]. Contributing factors may include repetitive strain, poor ergonomic conditions, or injuries sustained during work.

In semiconductor manufacturing, wafer preparation processes are critical stages that involve intricate tasks requiring precision and skill. Table 3 highlights that 100% of workers are engaged in tasks involving awkward postures and repetitive motions, both of which are key contributors to ergonomic challenges. Notably, workers spend a significant portion of their time with their necks raised upward, particularly during the wafer patterning process. Workers assigned to this process typically dedicate three to four hours per day to the task, making it the most time-intensive operation compared to other tasks.

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Table 3: Work Setting Data

No	Variable	Classification	Frequency (Job Tasks)				Percentage (%)			
			Load the lot	Carry the lot	Wafer Patterning	Wafer Inspection	Load the lot	Carry the lot	Wafer Patterning	Wafer Inspection
1	Duration of work per day	8 hours (3shifts)	2	2	2	2	100%	100%	100%	100%
2	Hours of break	≤ 1 *hour*	2	2	2	2	100%	100%	100%	100%
		≥ 1 hour	0	0	0	0	100%	100%	100%	100%
3	Posture adapts more at work	Standing	2	2	2	2	100%	100%	100%	100%
		Sitting	0	0	0	0	100%	100%	100%	100%

In terms of physical demands, the posture adapt more at work is standing as reported by the workers. Standing positions are generally preferred in semiconductor manufacturing due to the precision, focus, and nature of the tasks. Standing offers greater flexibility and freedom for movement, enabling workers to adjust their posture as needed, which may not be feasible in a sitting position. During wafer patterning, workers typically inspect 25 wafers per lot, spending approximately three hours to complete the inspection process. This demanding task underscores the physical challenges workers face in ensuring the process meets stringent quality standards.

Research in the electronics manufacturing industry revealed that repetitive operations, combined with awkward neck and wrist postures, significantly increased the risk of work-related musculoskeletal disorders (WMSDs) [101]. Workers engaged in repetitive tasks, such as those in wafer patterning, often experience strain in the neck due to prolonged upward tilting of the head, as well as wrist pain caused by repetitive hand movements during inspection and handling of wafers. Additionally, all workers reported taking a one-hour daily break, providing an opportunity for rest and recovery. However, while the uniform break policy ensures some level of rejuvenation, its effectiveness in mitigating the physical strain from prolonged standing remains limited.

4.3 Musculoskeletal Symptoms (NMQ Findings)

The Nordic Musculoskeletal Questionnaire (NMQ) results revealed notable patterns of musculoskeletal discomfort among operators. Both workers reported symptoms in the neck, wrists/hands, upper back, and lower back within the past 12 months and during the last 7 days. These symptom regions correspond strongly with key ergonomic exposures observed during wafer patterning—namely sustained neck extension, repetitive hand movements, and prolonged static standing. One operator also reported discomfort in the hips/thighs, lower legs, and ankles/feet, reflecting the strain associated with extended standing on rigid cleanroom flooring. Importantly, both operators indicated that several regions of discomfort—including the neck, upper back, lower back, and wrists/hands—had at some point interfered with their ability to carry out normal work activities. This supports the presence of genuine functional impact rather than mild or temporary discomfort. The clustering of symptoms in weight-bearing and posture-dominant areas highlights the cumulative physiological burden placed on operators during extended wafer patterning cycles.

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4.4 Initial ERA Screening

The Ergonomics Risk Assessment (ERA) checklist provided the first structured evaluation of risk factors across wafer preparation tasks. The screening showed that the loading and carrying tasks, although involving awkward postures and moderate manual handling, did not consistently exceed the minimum criteria for advanced assessment. Similarly, wafer inspection exhibited awkward neck and upper-back postures but did not present repetitive or sustained exposures severe enough to trigger formal escalation for both workers. However, the wafer patterning task met the advanced assessment threshold in two primary domains: static and sustained postures, and repetitive movements. This was expected given that operators perform repetitive fine motor tasks and maintain standing and neck-extended postures for approximately three hours per lot. The alignment of ERA scores with NMQ symptom patterns validated wafer patterning as the most critical workstation warranting in-depth biomechanical analysis.

4.5 Postural Risk Evaluation (REBA Results)

The REBA assessment quantified the severity of postural risks during wafer patterning. Worker 1 and Worker 2 scored 9 and 10, respectively, placing both operators in the "high-risk" category that necessitates corrective action in the short term as shown in Table 4. These high REBA scores were driven by a combination of non-neutral neck postures—particularly cervical extension required to view a monitor positioned above eye level—forward trunk inclination, static lower-limb posture, and elevated upper-arm and wrist positions during equipment control and monitoring. Sustained static loading of the neck, shoulders, and spine during the three-hour patterning cycle significantly increases musculoskeletal strain and contributes to long-term risk of degenerative changes. The integration of REBA results with NMQ findings provides strong evidence that workstation design factors, especially visual display height and lack of movement, are central contributors to high ergonomic risk at the patterning station.

Table 4: REBA Scores

Steps	Position	Worker 1	Worker 2
Step 1	Locate Neck Position	3	3
Step 2	Locate Trunk Position	3	4
Step 3	Legs	2	1
Step 4	Look-up Posture Score in Table A	6	6
Step 5	Add Force/load Score	0	0
Step 6	Score A, Find Row in TableC	6	6
Step 7	Locate Upper Arm Position	3	4
Step 8	Locate Lower Arm Position	1	2
Step 9	Locate Wrist Position	3	3
Step 10	Look-up Posture Score in Table B	5	7
Step 11	Add Coupling Score	0	0
Step 12	Score B	5	7
Step 13	Activity Score	1	1
REBA Score		9	10
Exposure Level		High Risk, Investigate and Implement Change	

4.6 Repetitive Motion Analysis (ART Results)

The ART assessment revealed major disparities between left and right upper limb exposure as shown in Table 4.5. Because both operators are right-hand dominant, the right arm performed

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more frequent clicking, typing, and parameter adjustments, resulting in significantly higher exposure scores (25–26) compared to the left (12–13). ART classifies these right-arm scores as presenting high ergonomic risk requiring urgent corrective measures. Factors contributing to these scores include repetitive movement frequency, moderate force exertion through gloved hands, non-neutral wrist deviation during mouse and keyboard use, and elevated arm posture kept away from the torso for extended periods. The neutral-position deviation of the wrist—scored as 2 for both workers—confirms that repetitive fine motor tasks are executed with mechanically inefficient joint alignment. The limited opportunities for rest within the three-hour cycle further magnify cumulative strain. These findings reinforce that repetitive motion injury risk is pervasive, particularly in the dominant upper limb, and must be addressed through both workstation redesign and task-organization strategies.

Table 5: REBA Scores

Risk factors	Left arm		Right arm	
Workers	**Worker 1**	**Worker 2**	**Worker 1**	**Worker 2**
A1 Arm movements	0	0	3	3
A2 Repetition	0	0	3	3
B Force	0	0	A2	A2
C1 Head/neck posture	2	2	2	2
C2 Back posture	1	2	2	1
C3 Arm posture	2	2	4	4
C4 Wrist posture	2	2	2	2
C5 Hand/finger grip	0	0	2	2
D1 Break	4	2	4	4
D2 Work pace	1	1	1	1
D3 Other factors	1	1	1	1
Task score	13	12	26	25
D4 Duration multiplier	X1	X1	X1	X1
Exposure score	13	12	26	25
Exposure Level	Medium (Further Investigation Required)		High (Further Investigation Required Urgently)	

4.7 Root Cause Analysis of Ergonomic Risks

Figure 2 and 3 illustrates the static awkward posture and repetitive motion respectively highlighting the various causes associated with this posture. The root causes of static awkward posture can be traced to several interconnected factors. People often lack sufficient training and awareness regarding ergonomic practices, which are crucial for preventing discomfort and long-term health problems. Without a proper understanding of posture management, many workers unintentionally adopt unhealthy habits during tasks, especially in fast-paced or high-pressure work environments where maintaining good posture becomes more difficult. The process involved in tasks can further exacerbate ergonomic challenges; for instance, tasks that demand prolonged focus for hours without adequate breaks can lead to fatigue and strain, significantly increasing the risk of physical discomfort, reduced efficiency, and long-term musculoskeletal issues. Additionally, the equipment used in the workspace plays a major role in the problem.

Poorly positioned workstations, such as computers placed above eye level, force workers into static awkward postures that lead to discomfort and potential injury over time. Lastly, management plays a pivotal role in addressing these issues. A lack of clear policies and guidelines on workplace ergonomics, along with insufficient investment in ergonomic equipment or

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employee welfare programs, reflects a failure to prioritize worker health and safety. Furthermore, the absence of structured training programs and ergonomic monitoring increases the likelihood of poor posture habits and workplace injuries, affecting both productivity and well-being.

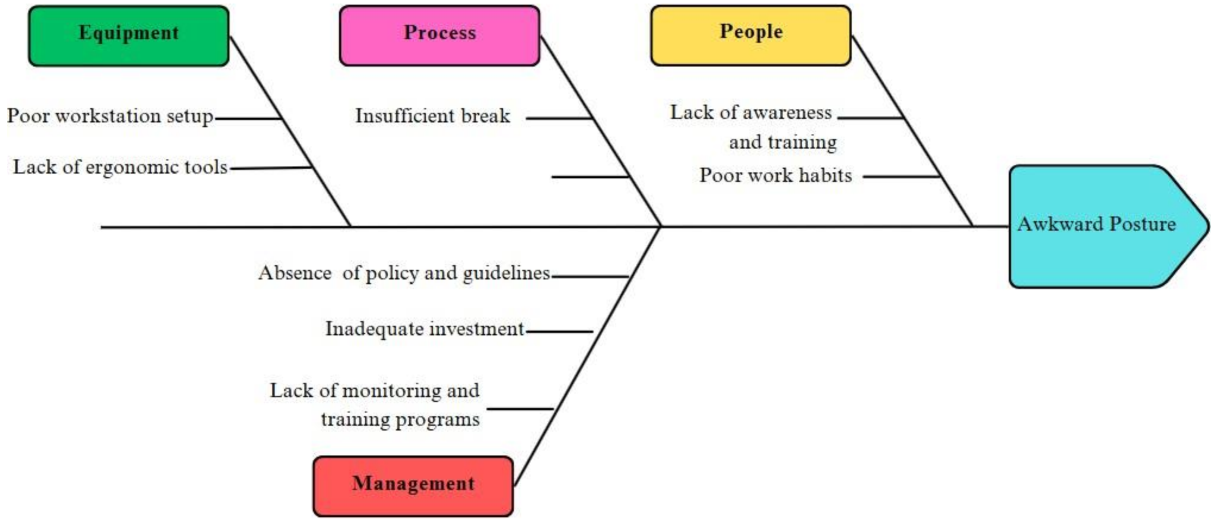

Figure 2: Fishbone diagram for static awkward posture

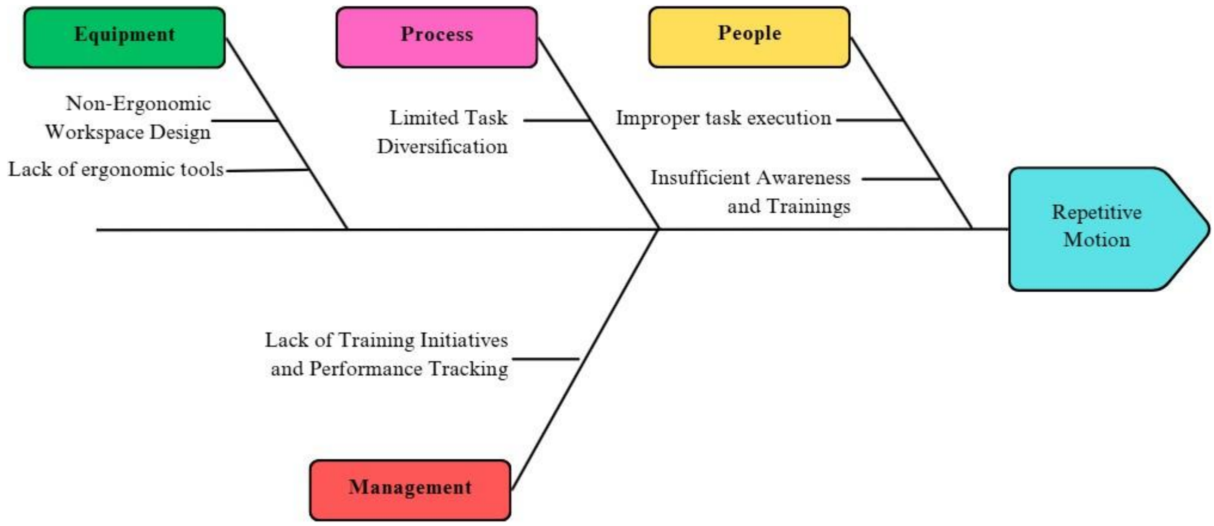

Figure 3: Fishbone Diagram for Repetitive Motion

The root causes of repetitive motion in wafer patterning monitoring can be traced to several interconnected factors. People often perform tasks with improper posture and insufficient rest breaks, leading to repetitive strain injuries. Continuous use of keyboards and mice without adequate micro-breaks increases muscle fatigue and joint stress, and many workers lack awareness and training on proper ergonomic practices, including correct hand positioning, posture adjustments, and the importance of stretching exercises. This knowledge gap, combined with the absence of ergonomic habits, contributes to discomfort, reduced efficiency, and a higher risk of long-term musculoskeletal disorders (MSDs). The task process itself exacerbates the problem by involving highly repetitive motions, such as clicking, typing, and making fine motor adjustments, which require the same hand and wrist movements for extended periods. The lack of task variation forces workers to engage the same muscle groups repeatedly without sufficient recovery time, increasing the risk of cumulative trauma injuries. The absence of structured task

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rotation and scheduled micro-breaks only prolongs exposure to these repetitive motions, leading to muscle fatigue, joint strain, and eventual injury. Equipment also plays a significant role, as workstations that are not ergonomically optimized force workers to perform repetitive motions in unnatural postures for long hours. Improperly positioned monitors, keyboards, and mice lead to continuous strain on the wrists, arms, and neck, accelerating muscle fatigue and increasing the risk of repetitive motion injuries. Finally, management is a crucial factor in addressing these issues; the lack of clear policies, structured training programs, and performance tracking leaves workers unprepared to adopt proper ergonomic practices or utilize available tools effectively. This oversight limits the ability to monitor compliance and address areas needing improvement, ultimately increasing the risk of injuries and negatively impacting workplace productivity and overall efficiency.

4.8 Proposed Ergonomic Improvements

Effective mitigation of ergonomic risks at the wafer patterning workstation requires a combination of engineering and administrative interventions. Engineering controls focus on modifying the physical environment to reduce biomechanical load at its source. These include installing height-adjustable monitor mounts to position screen height at or slightly below eye level, introducing cleanroom-compatible sit–stand stools or adjustable chairs to alternate between seated and standing postures, and adding anti-fatigue mats to increase lower-limb micro-movement and reduce foot and spinal loading. Reconfiguring input device placement to maintain neutral wrist posture is also essential. Where feasible, partial automation of repetitive actions through robotics or semi-automated interfaces could substantially reduce upper-limb repetition.

Administrative controls complement these physical modifications by shaping work behaviors and organizational practices. Structured ergonomic training would help operators recognize and correct poor postures and adopt healthier wrist and arm alignment techniques. Introducing scheduled micro-breaks every 1–2 hours, accompanied by simple stretching routines targeting the neck, shoulders, back, wrists, and lower limbs, can improve circulation and reduce fatigue. Job rotation—alternating wafer patterning duties with less repetitive or less posturally demanding tasks—can also substantially decrease cumulative exposure. Implementing periodic symptom monitoring through tools such as the NMQ ensures early detection of emerging strain and enables proactive adjustment of workload or workstation conditions.

5. CONCLUSION

In conclusion, this study provides important insights into the ergonomic challenges present in wafer preparation processes, particularly within the wafer patterning workstation where the highest physical strain was identified. The combined use of initial and advanced ergonomic assessment tools revealed that workers are exposed to substantial risks involving awkward postures, prolonged standing, and highly repetitive upper-limb movements. These findings align with broader ergonomic research indicating that tasks requiring sustained neck extension, repetitive wrist actions, and static lower-body postures significantly increase the likelihood of Work-Related Musculoskeletal Disorders (WMSDs).

Advanced assessments such as REBA and ART were particularly effective in quantifying the severity of these risks. High REBA scores for both workers demonstrated a clear need for immediate ergonomic interventions, while ART evaluations revealed that repetitive tasks involving the dominant hand impose a medium to high level of strain. These tools not only validated the workers' reported discomfort but also highlighted specific biomechanical stressors that contribute to cumulative musculoskeletal load. Such data-driven evaluations are essential for developing interventions that directly target root causes rather than merely treating symptoms of ergonomic strain.

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However, addressing these ergonomic risks requires more than just assessment; it demands a strategic and multifaceted approach. Engineering controls including height-adjustable workstations, sit-stand support systems, and anti-fatigue flooring offer practical solutions that can significantly reduce physical strain by encouraging neutral postures and minimizing static load. The potential integration of automation and robotics also represents a promising direction, as automated handling and inspection systems can reduce the need for repetitive manual movements and prolonged visual focus. Administrative controls are equally important; structured stretching programs, job rotation schedules, and routine ergonomic training help reinforce safer work habits and reduce the cumulative effects of repetitive strain.

Despite the effectiveness of current interventions, several challenges remain. Semiconductor manufacturing environments impose strict spatial, cleanliness, and process constraints that can limit the feasibility of certain ergonomic redesigns. Additionally, prolonged shift durations and increasing production demands amplify physical fatigue, indicating a need for further study on the relationship between workload, recovery time, and ergonomic injury risk. As wafer fabrication technologies continue to advance, it is essential that ergonomic practices evolve alongside them, ensuring that workplaces remain not only efficient but also safe, adaptive, and human-centered.

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