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Developing an ergonomic model and automation justification for industrial spraying operations: A case study

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Developing an ergonomic model and automation justification for industrial spraying operations: A case study

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Abstract

Industrial spraying tasks prove to be some of the most dull, dirty, and dangerous jobs in the modern day. Although it is a ripe area for automation, justification methods do not typically account for the potential improvements in the ergonomics of a task from automating it. In addition, there is a gap in the ergonomics literature in formal methodologies to comprehensively evaluate an industrial spraying task ergonomically, including all relevant musculoskeletal elements. This research focuses on first developing a formal, comprehensive methodology for ergonomically evaluating industrial spraying tasks and attaining a final classification of the ergonomic ranking of the task. Then, this research shifts to applying this methodology in a case study format to an industrial spraying task at a manufacturing plant, and the results will be analyzed. Specifically, this research will then focus on how the results of the ergonomic analysis can be used to drive the justification and design of potential automated solutions to improve the ergonomics of the task for the worker. This analysis will show how ergonomics can be a viable and measurable factor in justifying automated solutions to industrial spraying tasks.

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1. Introduction

Robotics and automation have saved countless lives since their inception in the early 1960s, from improving a variety of detailed surgeries by providing more high precision operations to patients [1], to getting humans out of the highly dangerous job of handling hazardous waste material. With the advent of advancing robotic technologies, there is growing interest in being able to have robots perform dull, dirty, and dangerous jobs that, in many cases, people do not even desire to have. However, before implementing or even piloting a robotic solution, companies almost always require some sort of justification [2]. This process usually involves an economic justification related to the return on investment of the automation investment. However, the justification can also be related to other areas, such as the perceived value the automation adds to business. One often overlooked piece and vital part of this justification for automation involves the safety and human factors (ergonomics) of the job that is being considered for automation (or semi-automation). In fact, very few justification methods for automation focus on the actual ergonomics (human posture, working conditions, etc.) of a job. Could ergonomics be used in the justification process for automation, particularly for dirty and dangerous jobs?

Industrial spraying operations constitute some of the most dirty and unpleasant jobs across industries. According to the United States Bureau of Labor and Statistics, industrial spray painting alone has over 160,000 workers and a higher rate of injuries and illnesses than the national average rate for all jobs [3]. This fact is not surprising, given that industrial spraying jobs tend to be in hot, dirty, dangerous, toxic, and physically straining environments. As shown in Figure 1 below, workers typically wear hazmat suits, work in non-air-conditioned environments, encounter harmful chemicals in the air, and hold awkward, straining body positions for extended periods of time.

Figure 1: Example of an industrial spraying operation performed by a worker

An industrial spraying operation, as defined by The Occupational Safety and Health Administration (OSHA), is "the employment of methods wherein organic or inorganic materials are utilized in dispersed form for deposit on surfaces to be coated, treated, or cleaned" [4]. This spraying operation category encompasses various industries including the construction, shipyard, marine, and general industries, and includes a wide array of activities from spray painting a finished automotive to pressure washing dirty parts at a military facility. According to OSHA, the injuries and illnesses rates of equipment and coating painters is higher than the national average [3, 5] These relatively high injury and incidence rates may result from inadequately addressing the long, diverse list of both short and long-term health risks that industrial spraying operations pose to workers. These risks including lung cancer, permanent brain damage, burns, various cancers, muscular injuries, kidney damage, and liver damage [6]. If the many risks associated with industrial spraying operations are not properly evaluated and addressed, workers are faced with serious and potentially deadly health risks. In addition to these environmental risks and hazards, workers still face risks of developing severe MSDs (musculoskeletal disorders), such as tendonitis in their hands, from holding spraying equipment in unnatural positions for extended periods of time [7].

While many government safety organizations, such as OSHA, have outlined many of the environmental risk areas for industrial spraying operations, such as harmful exposure to chemicals, heat stress, and lack of ventilation for workers [8], many of these organization's evaluations do not emphasize and incorporate the physical ergonomics (e.g. body posture, required grip forces, etc.) of industrial spraying applications. In addition, many of these evaluations make it arduous for a non-technical worker to perform the ergonomic evaluation, and just give guidelines for measuring one aspect of the job (e.g. measuring the heat stress of a worker), instead of incorporating the relevant measures into an overall measure of the ergonomics of the job. For example, ergonomic studies may reveal that the risk to exposure to toxic chemicals is negligible, but the risk of heat stress is large. There is currently not a way to combine these two measures, in this simple example, into a combined score, which gives the overall ergonomic measure for the job. Thus, there is a need in the ergonomics field and literature for a more understandable, simple, effective, and musculoskeletal-focused ergonomic methodology and tool for evaluating an industrial spraying job by incorporating different measures into a combined ergonomic score. Could a newly developed, ergonomic, musculoskeletal-focused methodology and scoring tool be used to justify the automation of an industrial spraying task by comparing the score pre-automation to the predicted score post automation? This research aims to answer these posed questions and fill the gaps in the literature in the area of the ergonomic justification for automation.

The objectives of this research are as follows:

1. Develop a methodology and tool to measure the ergonomics of industrial spraying operations, that focuses on the muscular skeletal hazards instead of mainly the environmental risks, and is intuitive enough for someone without an ergonomics background to use.
2. Use this methodology to evaluate the ergonomics of an industrial spraying operation before and after partially automating the task.
3. Provide a justification for automation based on the results of these ergonomic evaluations.

2. Literature Review

The goal of this literature review is to gain an insight into the current methods and research in (1) justifying automation, specifically based on the ergonomics of a job, and (2) evaluating the ergonomics of an industrial spraying operations, with a particular emphasis on the musculoskeletal aspects of a job. Each of these literature sections are explored further, below.

i. Automation justification methods

Traditionally, justifications for automation revolve around economic elements such as ROI or cash flow analyses. These justification methods prove to be an issue in justifying many automation solutions, because the advantages from implementing some automated (or semi-automated) solutions may not be easy to quantify or calculate in monetary terms [9]. This problem has been researched before, and the different methods of justification have been explored, such as economic, analytic, and strategic approaches [2]. Although these different approaches explore different methods for scoring the benefits of an automated solution, they still focus mainly on the operational benefits of the solution (i.e. costs, ROI, quality of product, product flexibility, etc.), as shown in Figure 2 below.

	Project Number			
Factor	1	2	3	
ROI 15%	x		x	x
Compatibility	x	x	x	
Improving Quality			x	
Total Score	2	1	3	1

Figure 2: Example of scoring model, incorporating only operational benefits from automation

Other research has been done in using different types of scoring models to account for a variety of other operational benefits to consider, such as competitive position, throughput times, and capacity. Although these methods incorporate more factors into the automation decision, they are still lacking the ergonomic evaluations of a job that is being considered for automation. Also, ergonomic factors usually cannot be easily incorporated into a scoring model and into an overall score easily, as indicated by previous ergonomic research in combining different ergonomic factors into an overall score [10]. The problems in combining ergonomic measures are usually due to the interactions between the measures that prevent them from being used in simple weighted factor model calculations. Thus, there is a gap in the literature in methods that use ergonomics measures of a job to find a combined value to use in justifying the automation of that job. In addition, there is also a need in the literature for this methodology applied in a case study setting, and used in the actual justification for automating a task. One of the unique contributions of this research is a methodology that uses ergonomic measures of a job to justify it for automation (or semi-automation), and an example of this methodology applied in a relevant case study setting.

ii. Ergonomic evaluation methods for industrial spraying applications

Industrial spraying jobs, which are typically dull, dirty, toxic, and dangerous, currently are and have been excellent candidates for automation. Current ergonomic evaluation methodologies for industrial spraying operations mostly focus on either the environmental factors personal equipment (sprayers, personal protective equipment, etc.) [10]. The literature discussing the environmental factors includes topics such as harmful chemical exposure, ventilation, and personal protective equipment, to protect the worker [8]. The second main area of focus in the ergonomics of industrial spraying operations includes technical tool design research to improve the ergonomics of spraying equipment to reduce the stress and awkward positions of workers' hands and wrists. While both of these two areas are fundamental and crucial for assessing the overall ergonomics of industrial spraying operations, the third factor of assessing the physical stresses and risks for the worker, is lacking in attention. Although the ergonomics literature is lacking musculoskeletal-focused, formal ergonomic methodologies to evaluate industrial spraying operations, there are tools developed to assess the main areas of safety concern for industrial spraying operations. These specific areas include (1) overall environmental, (2) wrist stress, (3) posture (back, shoulders, neck, etc.), and (4) heat. For each of these areas of concern, there are ergonomic tools to assess each area individually. For example, the OSHA injury incidence rate addresses environmental risks. The job strain index assesses risks to the wrist. The WISHA posture screening tool evaluates posture related risks, and the Health and Safety Executive's heat stress checklist measures the risks of heat stress on workers performing any job. Part of the ergonomic framework must include a way to combine different measures or outcomes from ergonomic tools into an overall score to be used to evaluate the overall ergonomics of an industrial spraying operations. The American National Standards Institute (ANSI) has developed a standard, ANSI/RIA R15.06-1999, that combines safety elements of a robotic work cell into an overall score, which is used to assess and mitigate risks to the work cell [18]. This tool and approach is unique, because both allow for the scoring of factors that may have interactions between them, which cannot be scored using traditional weighted factor or numerical models.

There are some current examples of musculoskeletal-focused ergonomic evaluations of industrial spraying operations in the literature, but this research focuses on applying general ergonomics principles to the unique situation, or case studied. One example of these specific applications is a physical evaluation of spraying operations in the woodworking industry, which found that workers were at high risk for developing MSDs in their hands and wrists from awkward positioning and high forces, resulting from holding the spraying equipment [12]. Researchers and ergonomists eliminated these MSD risks by applying standard ergonomic principles and creating fixtures, tables, and better tooling designs to reduce the unnatural postures and forces on the spray painters' hands for this unique task. Thus, there is a need in the literature for a more formal methodology to evaluate the physical ergonomics of industrial spraying operations that is clear enough to be performed by people, who do not have a background in ergonomics. Combining this need for a more musculoskeletal focused methodology for evaluating an industrial spraying operation, with the need for a methodology to justify the automation of a task based on its ergonomic evaluations, leads to the center of this research. This research will meet the two main needs mentioned above by providing a methodology to evaluate an industrial spraying operation ergonomically, applying that methodology to a predicted future state automated work cell, and then using the results to provide a basis of justification for automating the evaluated task.

3. Problem Statement

The current robotics literature does not have robust, in-depth ways of including or evaluating ergonomics, when deciding whether or not to automate a certain activity. Additionally, more specifically, there is not an intuitive, comprehensive methodology in the ergonomics literature for evaluating the ergonomics of industrial spraying operations, specifically including musculoskeletal risks. Thus, there is a need for an ergonomic-based focus in the decision to automate a task and a more formalized musculoskeletal-focused ergonomic methodology to use to evaluate industrial spraying operations.

4. Methodology

This section explains the specific tools combined to address the four areas of concern for the safety and human factors of industrial spraying operations (environmental hazards, wrist stress, posture, and heat stress risks). First, each tool will be explained in-depth. Then, the case study industrial spraying job will be introduced. Finally, the methodology section will close with an explanation of a framework to combine these metrics into overall classifications to assist in justifying the automation of the industrial spraying task.

i. Tools for the ergonomic analysis

The methodology for the ergonomic analysis of industrial spraying operations were synthesized from the wealth of literature in the field of ergonomics. Although there are not many ergonomic measures specifically associated with industrial spraying operations, there are many methodologies for measuring different postures, muscle groups, and environmental factors. The problem, then, was figuring out which tools to combine into this methodology to adequately assess all relevant aspects of the ergonomics of industrial spraying tasks, with a specific focus on the musculoskeletal aspects of the job. From the current literature on the human factors of industrial spraying tasks, it was evident that the ergonomic risks consisted of the two areas, listed in Table 1 below.

General Risk Area	Details
Environmental [8]	Exposure to chemicals in the air, heat, burns, etc.)
Musculoskeletal [12]	Musculoskeletal disorders (MSDs)in the wrists, back, hands, shoulders, and other upper extremities

Table 1: General Risk areas for industrial spraying tasks, from the literature

Using this research knowledge, it was determined that the ergonomic measures should specifically focus on the more detailed areas, listed below in Table 2. The measure or tool for each of these areas is shown in the 'Measure' column in Table 2. In the following sections, each measure will be explained further.

Risk Area	Details	Measure
Overall environmental risk	Examples include exposure to harmful chemicals and substances [8]	OSHA recordable injuries and illnesses rate [13]
Wrists and hands	Loads experienced by the wrists and hands, specifically from holding heavy equipment in unnatural postures [12]	Job Strain Index (JSI) [14]
Postures (Lower Back and upper extremities)	Industrial spraying operations typically force people to hold unnatural positions with [12]	Washington State Screening Tool [15]
Heat risk	These tasks typically require workers to work in not air-conditioned environments in non-permeable protective clothing (ex- HAZMAT suit) [8]	Heat Stress tool from the Health and Safety Executive [16]

Table 2: Specific risk areas and their measures, for industrial spraying operations

a. OSHA non-fatal occupational injuries and illnesses incidence rate

OSHA, being the main government body that monitors job safety in the United States, has developed a variety of measures to determine how safe a task is. The non-fatal occupational injuries and illness incidence rate is defined as "the number of employees per 100 full-time employees that have been involved in a recordable injury or illness" [17]. This incidence rate is a great measure to compare the relative safety of a task across companies and industries [13]. Thus, this incident rate measures and covers the general environmental risks of industrial spraying tasks, such as slips, falls, injuries from equipment, and muscle strains. In order to interpret the incidence score, certain general thresholds are given by OSHA, as shown in Figure 3, below. For example, a rate above 8 would be considered to be in the most dangerous category for environmental hazards. Hazard would be interpreted as dangerous, caution would be risky, and no risk would be safe. In addition, industry standards can be used to evaluate an OSHA incidence rate score. For example, the average OSHA incidence rate across the manufacturing industry in Texas can be used to benchmark acceptable OSHA incidence rates for manufacturing facilities in Texas.

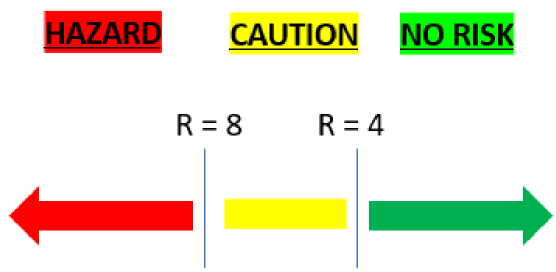


Figure 3: Example of general thresholds for OSHA incidence rates (R)

b. Job Strain Index

Given that almost all industrial spraying tasks involve holding a pressurized piece of equipment to disperse the cleaning or coating substance, the hands and wrists of workers are at significant risk for developing a musculoskeletal disorder. The job strain index, developed by Cornell University's Ergonomics and Human Factors sector, measures the risk of injury to the hands and wrists based on the relevant factors of repetition, force, duration, and posture of the hands and wrists [14], as shown in Figure 4.

Job Strain Index Worksheet Example

	Intensity of Exertion (IE)	Duration of Exertion (DE)	Efforts/ Minute (EM)	Hand/Wrist Posture (HWP)	Speed of Work (SW)	Duration per Day (DD)
Exposure data	Somewhat hard	60%	12	fair	fair	4-8
Ratings	3.0	2.0	1.5	1.5	1.0	1.0

$$JSI = IE \times DE \times EM \times HWP \times SW \times DD$$

$$JSI = 3.0 \times 2.0 \times 1.5 \times 1.5 \times 1.0 \times 1.0$$

$$JSI = 13.5$$

Figure 4: Example of the Job Strain Index Evaluation tool for the hands and wrists [14]

To classify the rating, or level, of each measure in the job strain index tool, the job strain index tool provides a table with ratings and their various levels. For example, the column for the intensity of the exertion (1st part of the job strain index tool) was attained by using the table for this measure, and using the descriptions to best classify the activity being studied. One example of one of these tables for a measure is shown in Figure 5 below. Note, the rest of the tables for the other measures can be found in the actual tool, or in the Appendix.

1. Intensity of Exertion

An estimate of the strength required to perform the task one time. Guidelines for assigning a rating criterion are presented in the following table.

Rating Criterion	% MS[A]	Borg Scale [B]	Perceived Effort
Light	<10%	<=2	barely noticeable or relaxed effort
Somewhat Hard	10%-29%	3	noticeable or definite effort
Hard	30%-49%	4-5	obvious effort; unchanged facial expression
Very Hard	50%-79%	6-7	substantial effort; changes facial expression
Near Maximal	>=80%	>7	uses shoulder or trunk to generate force

[A] Percentage of maximal strength

[B] Compared to the Borg CR-10 scale[78]

Figure 5: Job Strain Index table for the 'intensity of exertion' measure [14]

After using the provided tables to evaluate the other parts of the job strain index, the user assigns the appropriate score for each part of the tool, based on the category chosen for each measure, using the table shown in Figure 6, below. For example, if the user rates the intensity of exertion as "light", then the corresponding score for the tool would be a 1. The number in parentheses below the categorical description gives the numerical score for each measure. Then, the user multiplies all six numbers together to achieve an overall score, which is interpreted using a similar scale as shown in the OSHA incidence rate example. Job Strain Index scores greater than 7 are the most dangerous, and are likely associated with musculoskeletal disorder development in the wrists, such as carpel tunnel syndrome [14]. The other thresholds to use when assessing the final score are shown below in Figure 7.

Job Strain Index

Rating	Intensity of Exertion (IE)	Duration of Exertion (DE)	Efforts/ Minute (EM)	Hand/Wrist Posture (HWP)	Speed of Work (SW)	Duration per Day (DD)
1	Light (1)	<10% (0.5)	<4 (0.5)	Very good (1)	Very slow (1)	<1 (.25)
2	Somewhat hard (3)	10-29% (1)	4-8 (1)	Good (1)	Slow (1)	1-2 (.5)
3	Hard (6)	30-49% (1.5)	9-14 (1.5)	Fair (1.5)	Fair (1)	2-4 (.75)
4	Very hard (9)	50-79% (2)	15-19 (2)	Bad (2)	Fast (1.5)	4-8 (1)
5	Near maximal (13)	80-100% (3)	>=20 (3)	Very bad (3)	Very fast (2)	>=8 (1.5)

$$JSI = IE \times DE \times EM \times HWP \times SW \times DD$$

Figure 6: Job Strain Index table to assign each measure's number, based on the user's assessment [14]

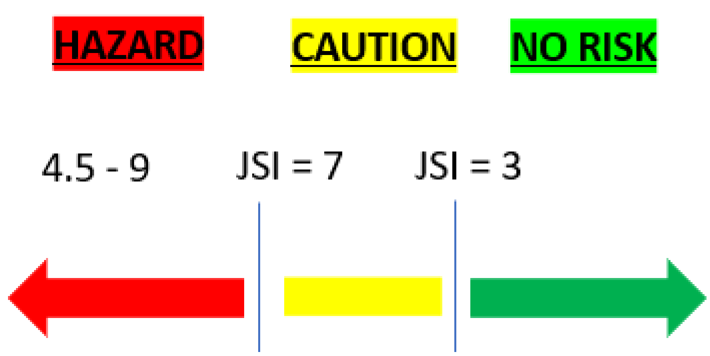


Figure 7: Thresholds to use to interpret results from the Job Strain Index final score

This tool is a great fit to use for assessing an industrial spraying operation, because of workers' high usage of hands and wrists while performing a spraying task. This specific focus on the ergonomics of the specific musculoskeletal area of the hands proves to be an essential contribution to the ergonomics literature in industrial spraying tasks.

c. Washington State (WISHA) screening tool

To address the ergonomic concerns with the unnatural postures so relevant in industrial spraying tasks, the Washington State Screening Tool is used, because of the variety of postures and hazards that it addresses. This tool accounts for many muscle groups and their postures, ranging from the knee region all the way to the neck. It determines whether a task is a caution, hazard, or safe, by assessing the time per shift that the operator must spend in a certain position. For example, this tool indicates a lower back hazard if an operator must keep his or her back bent at an angle greater than 45 degrees for 4 or more hours per work day [15], as shown in Figure 8 below.

Low Back — **Overall: None Caution Hazard**

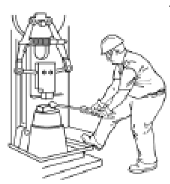
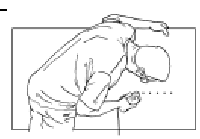
Posture			
Working with the back bent forward more than 30° (without support or the ability to vary posture)		More than 2 hours total per day.	Caution ❑
		More than 4 hours total per day	Hazard ❑
Working with the back bent forward more than 45° (without support or the ability to vary posture)		More than 1 hour total per day.	Caution ❑
		More than 2 hours total per day	Hazard ❑

Figure 8: Example of the WISHA screening tool for the lower back

The key advantage of the Washington State screening tool is the variety of muscle groups and postures it addresses. Table 3, shown below, shows all postures or measures of the WISHA screening tool. Each of these measures has its own dedicated description and section, like the lower back (posture) measure shown in Figure 8, above.

Number	Measure of the WISHA Tool
1	Lower Back- Posture
2	Weight/Force

3	Hands and Wrists- Pinch Grip
4	Hands and Wrists- Grasp Grip
5	Repetitive Motion of Hands
6	Keying
7	Hand Impacts
8	Hand-Arm Vibration
9	Neck and Shoulder- Neck Posture
10	Neck and Shoulder- Shoulder Posture
11	Neck and Shoulder- Repetitive Motion of Shoulder
12	Knee Posture
13	Knee Impacts

Table 3: Comprehensive list of measures in the Washington State screening tool

The Health and Safety Executive does not provide an official overall scoring system for the WISHA screening tool, but they do say that if one or more hazards are present, there needs to be immediate action taken to reduce the risk to the worker, because very poor ergonomic circumstances exist. In addition, if the results indicate many caution levels in each of the measure areas of the tool, there are still risks for the workers developing musculoskeletal disorders from performing this task. Thus, the following scale to interpret the results of the test, is shown below, in Figure 9. For example, if the results indicated a hazard in the lower back measure and a caution level in the hand impacts measure, then the final classification would be hazard.

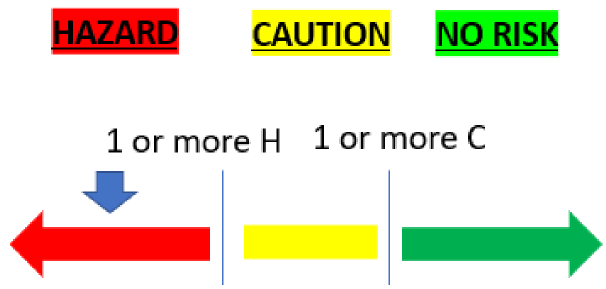


Figure 9: Scale to use to interpret the results from the WISHA screening tool (H stands for hazard, and C stands for caution)

d. Heat Stress Assessment from the Health and Safety Executive

Another major concern, specifically for industrial spraying tasks, is the risk of heat stress. This risk is enhanced for industrial spraying tasks, because operators typically wear moisture impermeable clothing and work in non-air-conditioned environments. Thus, because of this specific area of heat stress risk, a tool must be incorporated into the overall evaluation methodology to account for all relevant factors to measure the heat stress a worker experiences, while performing an industrial spraying job. The Health and Safety Executive, one of the main bodies of Great Britain that monitors worker safety, developed a heat stress assessment tool that considers all relevant factors that could lead to heat stress, such as air temperature, metabolic rate, heat coming from surrounding sources, etc. As shown in Figure 10 below, this heat stress tool guides the user in assigning a score to each of the relevant heat stress measures, and then gives an overall method for interpreting the results [16]. The rating of each measure is attained using the tables provided in the actual tool, such as the table for air temperature, shown below in Figure 11. The remaining tables for this tool are found in the appendix.

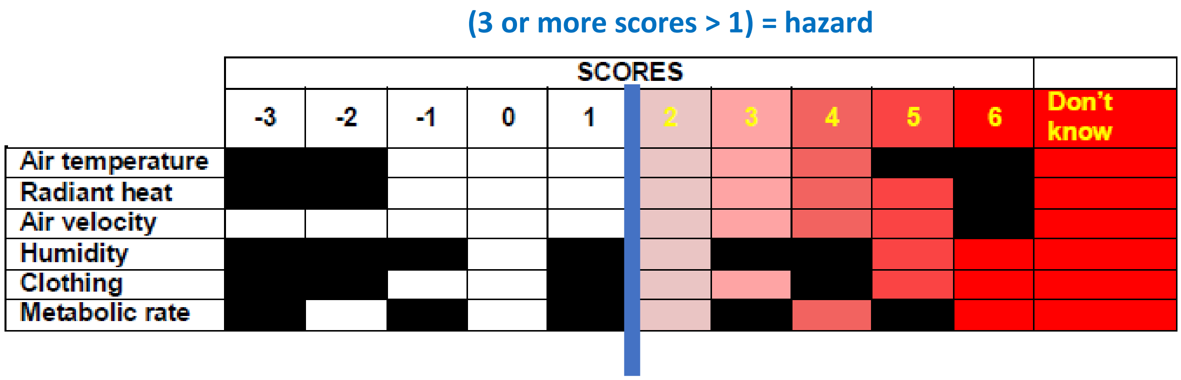


Figure 10: Example of the heat stress measures in the Health and Safety Executive's heat stress evaluation tool [16]

Air Temperature

What is air temperature and what should you look out for?

- Air temperature is described as the temperature of the air surrounding an employee.
- Consider the air temperature surrounding the employee and how you would describe it.

Subjective description of air temperature	Score	Tick
• Cool	-1	
• Neutral	0	
• Slightly warm	1	
• Warm	2	
• Hot	3	
• Very hot	4	
	Don't Know	

Figure 11: Example of the table to determine the rating for each measure in the heat stress assessment tool

The results can be interpreted by counting the number of areas where the score is greater than 1. For example, the overall heat stress ranking would be classified as a hazard if 3 or more measures resulted in scores greater than 1. The thresholds for each of the levels are shown below in Figure 12. This heat stress measure is combined with the other 3 ergonomic measures to constitute the ergonomic methodology for evaluating industrial spraying tasks.

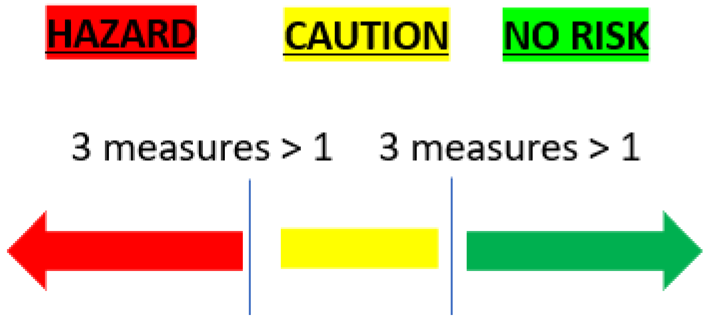


Figure 12: Scale to use to interpret the results from the Health and Safety Executive's heat stress assessment tool

ii. Application of the ergonomic methodology (Case Study)

This section aims to clarify and demonstrate the developed methodology in the context of a real-world case study. For the case study, this methodology was used to evaluate a real world industrial pressure washing task at a manufacturing facility. The facility's identity is kept confidential for privacy reasons.

a. The industrial spraying task studied

The industrial spraying operation analyzed in the case study consists of cleaning several types of small manufacturing, military parts using two pressure washing methods: (1) high temperature and (2) high pressure power washing. The main difference between these two types of pressure washing lies in the fact that the high-pressure method provides enough power to strip paint off parts, such as panels from vehicles. To effectively assess this industrial spraying task, it was essential to define the complete scope of the different spraying methods, because each method requires workers to use different spraying equipment with different ergonomics positions. For example, the high pressure spraying method had a longer spraying wand that allowed the operator to have a more straight back, than the high temperature method, which required the operator to bend over more. Finally, it is important to note that for this spraying task, 80% of the work requires the high temperature method, while 20% of the work requires the high-pressure method. This information was attained from the managers of this job area.

b. Ergonomic Measures and Data Collection

OSHA incidence rate calculation

The OSHA incidence rate proves to be a simple calculation, requiring the number of OSHA recordable injuries and illnesses and total number of worked hours (among all employees performing that job) over a period. Then, the formula standardizes the injury and illness data to span over 100 employees to allow companies to evaluate how safe a certain job is. The actual calculation is shown in the equation below.

$$IR\ (Incidence\ Rate) = \frac{Number\ of\ OSHA\ recordable\ injury\ or\ illness\ cases * 200{,}000}{Number\ of\ employee\ hours\ worked}$$

Equation 1: OSHA recordable injuries and illnesses equation [13]

For example, for the actual spraying job analyzed, there were 5 recordable injuries or illnesses recorded over a period of 2 years, in which 14 employees worked a total of 38,720 labor hours. These inputs were used to calculate the incidence rate for this task, and were used to analyze the overall safety of the work environment by comparing this number to industry standards. For this case study, the data needed (i.e. the recordable injuries and illnesses incidents over a certain period, and the total amount of work hours, worked by all employees, in that time), was attained from the safety and risk department at the manufacturing plant.

Job Strain Index calculation

The Job Strain Index calculation method first requires the analyst to use the relevant tables to classify each of the six measures of the tool (intensity of exertion, duration of exertion, etc.). Once each of the measures is rated as best as possible, the overall score is calculated by multiplying the six ratings together, to attain an overall job strain index score. This score indicates how hazardous the task is to the hands and wrists. Most of the measures were easy to rate, such as the speed of the work, duration per day, and efforts per minute. However, the intensity of the exertion was difficult to rate due to the subjectivity of the person performing the ergonomic analysis. Thus, providing a range of values (e.g. a 1 (light) or 2 (somewhat hard)) is sufficient, if it is difficult to decide between different categories. Finally, the duration of the exertion was calculated by taking a quick time study measurement of the wrist exertion of interest. In this case study, the exertion consisted of the wrist being activated from supporting the heavy spraying wand.

Using the Washington State (WISHA) screening tool

Using the Washington State Screening tool proves to be more arduous and comprehensive than the first two tools/measures were. Because the tool is designed such that the thresholds are measured in terms of the amount of time per day a worker spends in a certain posture, it is necessary to conduct comprehensive time studies of the spraying operation, as it is normally performed. In the following subsections, the data collection methodologies used will be explained further.

Conducting comprehensive time studies

The first key part of conducting these time studies is knowing the scope of the task being studied, and all the activities that constitute the entire task. For example, in the case study, I studied two types of spraying operations (high temperature and high pressure), each having about four different activities that required different postures and positions. Each activity had the tasks of moving parts, getting supplies, performing the actual spraying, and inspecting. Thus, it was crucial to take time study observations of a very typical mix of parts, where the operators performed all the tasks normally performed. These actions ensured that my time study observations were representative and very close to what the workers do almost every day. By ensuring the time study observations were comprehensive, I validated that my results could be extrapolated to this activity. The time studies performed were conducted using standard time study principles, recording all relevant information about the task, as well as the times and durations of the different activities the worker performed. This, in turn, was used to estimate the total time per shift a worker was in a certain posture (e.g. time per shift the worker's back was bent more than 45 degrees). There were two types of time studies performed. The first type was just a general time study of the different activities and their durations. This data could be used to assess how long the wrist was in a certain posture, because the wrist would be in that same awkward posture every time the operator was spraying parts. For example, if the operator sprayed parts 50% of the time from the time studies, in my case, I would know that the wrist was bent and in an awkward position with a slightly heavy load for roughly 50% of a worker's productive work day. The second type of time study was used for the postures that were not completely tied to a certain activity. For example, bending the lower back more than 45 degrees occurred during many of the activities, such as spraying, inspecting parts, and moving parts. So, a method was developed, where I recorded the running total of time the worker spent with his back bent over in a specific time interval. For example, if I was taking a ten-minute sample, I would have one timer for the duration of the 10 minutes, and then use a stopwatch to start and stop the time when the worker would be in the bent posture, or non-bent posture, respectively. By ensuring again that the second type of time studies encapsulated all the worker's activities, I was able to extrapolate the time study information to the overall job. The result of the time study data collection, were percentages that were used as proxies to estimate the total time per work day in a certain posture. It was crucial to use this proxy technique, because the data collection period only allowed for about four hours of time studies to be collected. To get the total amount of time spent in a certain posture, per shift, the % of time spent in that posture from the time studies was multiplied by the number of productive hours in a shift and then by the weight factor, which accounted for the type of spraying technique the worker was using (high temperature or high-pressure spraying). Figure 13, below, shows an example of the excel workbook and calculations for using this proxy method to determine the amount of time per shift that workers spent in the different, stressful postures. This data collection procedure was done for the other measures of the WISHA screening tool (i.e. lower back, shoulders, grip, etc.) in order to assess the time workers spend in those postures per shift.

Productive hours in a workday (hrs):	8.75	Legends:	Caution	
			Hazard	
Area	Description	% of time in this posture	Time per day in this posture (hrs)	
Lower Back	Working with the back bent forward more than 30° (without support or the ability to vary posture)	20.1%	0.35	
	Working with the back bent forward more than 45° (without support or the ability to vary posture)	65.6%	4.59	

$$Hours\ spent\ in\ \text{bent over}\ back\ posture\ per\ shift = \%\ of\ time\ spent\ in\ posture * working\ hours\ per\ shift * weighting\ factor$$

$$Hours\ spent\ in\ position\ per\ shift = 65.6\% * 8.75\ \text{hours} * 80\% = 4.59$$

Activity Details	Time with back bent more then 45 degrees without support (mins)	Total Time observed in the random sample (mins)
Inspecting and moving parts	2.60	5
Spraying	1.60	3
Getting Supplies and Spraying	3.93	4
Spraying and Inspecting	3.67	6
	11.80	18
	Total % of time spent with back bent more than 45 degrees	65.6%

Note, the %s were attained by taking random samples of how long the worker was in a given posture (e.g. back bent more than 45 degrees)

Figure 13: Example of the strategy for to use the time study data to determine the time the worker spends in each stressful posture per shift

Heat Stress Assessments

Similar to the first two tools (OSHA incidence rate and the job strain index), the heat stress tool is used by categorizing the different measures of the tool based on the descriptions. For example, I simply observed and stood in the area of work to gauge the air temperature of the task. Again, many of these classifications are subjective, but the user can distinguish the different categories from each other relatively easily. So, to collect the data to use the heat stress tool, the user needs to go to where the work is being performed to observe and feel the surrounding environment. Once each measure is classified, the corresponding score is assigned to the measure (e.g. a 1 for air temperature, 2 for air velocity, etc.). Finally, the scores are tallied and interpreted according to the scale presented above in Figure 12.

iii. Method for combining measures- EMIT model

Because these tools were combined as part of this research, to create a unique, intuitive methodology to evaluate industrial spraying operations, a methodology for combining the scores was derived. Due to the nature of the interactions between the different measures, a simple weighted factor model would not prove adequate for deriving an overall score for the overall ergonomics of the spraying task. For example, if three of the tools came out in the ‘no risk’ category, but the heat stress tool resulted in a hazard, a weighted factor model may categorize it as safe, when it is indeed hazardous, since just one of the measures was classified as a hazard. Thus, a more robust methodology is needed to classify the four tools as one overall score.

The American National Standards Institute (ANSI) provides a model and safety standard for Industrial Robots and Robot Systems, called ANSI/RIA R15.06-1999 [18]. In this framework, multiple classifications are combined into certain overall ranks, based on the levels of each classification, much like a decision branch and tree model. This framework is shown below in Table 4.

SEVERITY OF INJURY	EXPOSURE	AVOIDANCE	RISK REDUCTION CATEGORY
S2 Serious Injury More than First-aid	**E2** Frequent exposure	**A2** Not Likely	**R1**
		A1 Likely	**R2A**
	E1 Infrequent exposure	**A2** Not Likely	**R2B**
		A1 Likely	**R2B**
S1 Slight Injury First-aid	**E2** Frequent exposure	**A2** Not Likely	**R2C**
		A1 Likely	**R3A**
	E1 Infrequent exposure	**A2** Not Likely	**R3B**
		A1 Likely	**R4**

Table 4: ANSI/RIA R15.06-1999 Risk reduction classification matrix [18]

In addition to providing a means of classifying the different levels of each category (severity, exposure, avoidance) as an overall score, this ANSI framework provides requirements for improving the safety of the robotic work cell. It requires all R1 and R2 risk levels to be improved, so that they become R3 or R4 risk levels (very low risk). Regarding the task of combining my four ergonomic tools for the industrial spraying operations ergonomic analysis, the ANSI model provides an excellent inspiration and framework.

Thus, inspired by the ANSI/RIA R15.06-1999 risk management framework, I developed a model, called the EMIT (Ergonomic Measures Integration Tool) model, to combine the results of the four ergonomic tools into a combined metric. The definition of terms in the model are shown in Figure 15 and part of the actual model is shown in Figure 16, below. The rest of the model can be found in the appendix.

Legend 1	
H	Hazard
C	Caution
N	No Risk

Legend 2		Criteria
R1	Dangerous	2 or more H levels, or 4 caution levels
R2	Risky	1 H level, or 3 caution levels
R3	Moderate risk	2 caution levels
R4	Safe	1 or fewer caution levels

Figure 15: Definitions of terms and classification categories for the EMIT model

OSHA Rate	Job Strain Index	WISHA Posture Tool	Heat stress checklist	Combination of scores	Risk Level
H	H	H	H	HHHH	R1
			C	HHHC	R1
			N	HHHN	R1
		C	H	HHCH	R1
			C	HHCC	R1
			N	HHCN	R1
		N	H	HHNH	R1
			C	HHNC	R1
			N	HHNN	R1
	C	H	H	HCHH	R1
			C	HCHC	R1
			N	HCHN	R1
		C	H	HCCH	R1
			C	HCCC	R2
			N	HCCN	R2

Figure 16: Part of the actual EMIT model to combine the ergonomic metrics

This EMIT model contained the full list of potential outcomes all the possible scores of using the four tools. The “combination of scores” column contains the full combination of scores from the results of each individual ergonomic tool (OSHA incidence rate, job strain index, WISHA screening tool, and the heat stress tool), which is then used to assign the overall score to that combination. The scores range from R1 to R4, with R1 being the most dangerous ergonomically and R4 being the safest ergonomically. To use this tool, users would first get the results (Hazard (H), Caution (C), or No Risk (N)) from each of the four ergonomic tools, and then find the associated ranking using the model. Note, the ranking criteria for the model is shown in Figure 15. For example, R1 tasks have either 2 or more hazards or 4 cautions from the results from the four ergonomic tools. Thus, for example, an HHNN combination would result in an R1 classification, because it has two or more hazard levels. The rule for ergonomic risk reduction is all tasks that are rated as either an R1 or R2 must be reduced to an R3, or, ideally, an R4 (safe). Thus, this model provides an excellent framework and ergonomically-focused justification method for implementing an automated (or partially automated) solution, to improve the ergonomics of the task. The rule provided is that industrial spraying tasks that result in an R1 or R2 have much more justification for automation based on the ergonomics of the task, than tasks that result in an R3 or R4 score.

5. Results

In the results section, the actual case study results of the ergonomic analysis are presented and explained. In addition, the final scoring of the combination of each of the ergonomic measures, will be presented and discussed.

i. Current state ergonomic analysis case study- Results

a. OSHA injuries and incidence rate

The resulting OSHA incidence rate for the case study of the industrial spraying operation analyzed was 25.8. This was derived from using the OSHA incidence rate formula with 2 years' worth of data from the task studied. The interpretation of this number is that roughly 26 out of 100 employees would have a serious OSHA recordable injury or illness from this job in a span of two years. As shown in Figure 17, below, the result of R = 25.8 puts this task well over the threshold for a hazard, and is off the scale. In addition, this task has a much higher risk for environmental hazards compared to other manufacturing industries in Texas (the same state as the manufacturing facility from the case study). As shown in Table 5, the OSHA incidence rate for the task analyzed in the case study was much greater than the average OSHA incidence rate for manufacturing industries in Texas (25.8 compared with 2.8). Note, the Bureau of Labor and Statistics records and provides OSHA incidence rates of various industries to allow for safety benchmarking across industries [13]. Thus, the first tool results in a hazard classification (H).

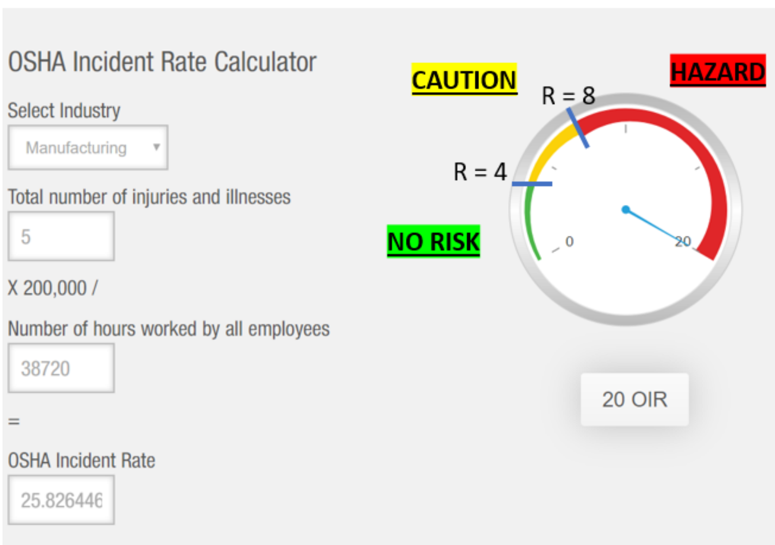


Figure 17: OSHA incidence rate metric current state results [14]

Company	OSHA Recordable Injuries and Illnesses Incidence Rate
Industrial Spraying Operation from Case Study	25.8
Other Manufacturing Industries in TX [1]	2.8

Table 5: Table comparing the OSHA incidence rates of the case study task with other similar industries in the same state

b. Job Strain Index

The scores from the job strain index assessment are shown in Figure 18, below. The scores for each of the 6 parts of the job strain index tool are shown in the rating row, along with the description for each classification below it. The job strain index assessment resulted in a range from 4.5 to 9, depending on whether the intensity of the task should be rated as somewhat hard or hard. For the purposes of this classification, the resulting overall classification will be the same whether this measure results in a hazard (H) or caution (C) ranking, so I will choose to classify it as a caution level. Thus, the final classification of the job strain index for this case study evaluation is a C.

	Intensity of exertion (IE)	Duration of exertion (DE)	Efforts /min (EM)	Hand/wrist posture (HWP)	Speed of work (SW)	Duration per day (DD)
Rating	3	2	0.5	1.5	1	1
	6					
Description:	Somewhat hard or hard	50-79%	<4	Fair	Slow	4-8 (hrs.)

JSI = IE x DE x EM x HWP x SW x DD

JSI = 3.0 x 2.0 x 0.5 x 1.5 x 1.0 x 1.0

JSI = 4.5 OR 9 (if IE is 6 instead of 3)

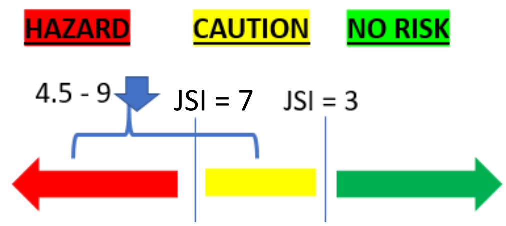


Figure 18: Job Strain Index current state analysis results

c. Washington State posture screening tool

The Washington State posture screening tool assessment resulted in 4 categories (measures) being in the hazard zone, and the rest of the ten measures being in the no risk zone, as shown in Table 6. In addition, because 4 measures of the tool were in the hazard zone, the total activity results in a hazard (H) ranking, as shown in Figure 19 below. Note, the raw time study data results used for this tool are included in the appendix.

Area	Description	Risk	Actual Results (hours per day)
Lower Back	Working with the back bent forward more than 45°	Hazard (> 2 hours per day)	4.6
Hands and wrists- Grasp Grip	Gripping Caution plus wrist deviation	Hazard (> 3 hours per day)	5.9
Hand-Arm vibration	Using grinders, sanders, jigsaws or other hand tools that typically have moderate vibration levels	Hazard (> 4 hours per day)	5.9
Neck Posture	Working with the neck bent more than 45°	Hazard (> 4 hours per day)	4.6

Table 6: Washington State posture screening tool current state results

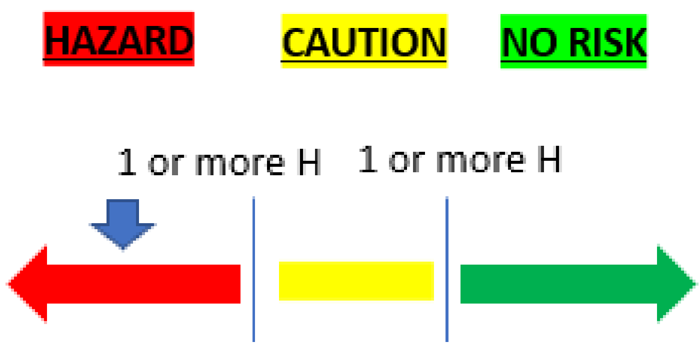
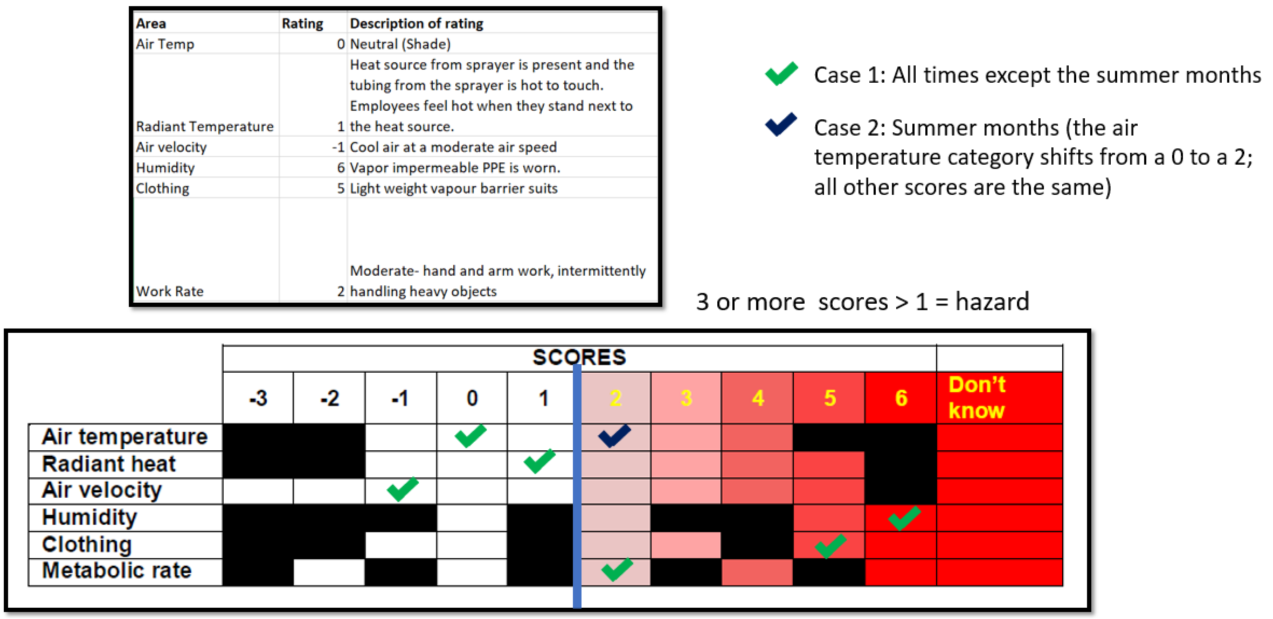


Figure 19: Score and results from the WISHA posture screening tool

d. Heat stress assessment tool

The heat stress assessment results indicated 3 measures above 1, and three measures below 1, as shown in Figure 20. The humidity, clothing, and metabolic rate measures put workers at risk for heat stress, while performing this industrial spraying operation. Note, that the observations for this heat stress assessment were taken on cool day, and air temperatures are much higher during summer months, when performing this spraying task. Thus, the blue arrow shows case 2, in the summer months, when it is very hot outside. This does not change the classification results, as the overall result from this heat stress tool is still a hazard level (H), because 3 or more of the heat stress measures are above 1 (Figure 21).



Area	Rating	Description of rating
Air Temp	0	Neutral (Shade)
Radiant Temperature	1	Heat source from sprayer is present and the tubing from the sprayer is hot to touch. Employees feel hot when they stand next to the heat source.
Air velocity	-1	Cool air at a moderate air speed
Humidity	6	Vapor impermeable PPE is worn.
Clothing	5	Light weight vapour barrier suits
Work Rate	2	Moderate- hand and arm work, intermittently handling heavy objects

Figure 20: Heat stress assessment tool results

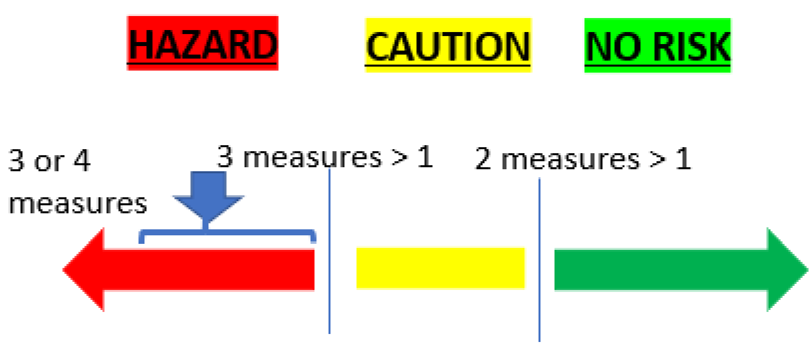


Figure 21: Score and results from the WISHA posture screening tool

ii. Overall EMIT model results of the current state analysis

The total combination of results from the four ergonomic analysis tools is HCHH. Using the EMIT tool (Figure 16), the user can read off that an HCHH combination results in an overall ergonomic analysis score of R1, the highest level of ergonomic risk. Thus, because the task resulted in an R1, steps should be taken to reduce the overall ergonomic risk to the worker. One main way to decrease these ergonomic risks is to automate or partially automate the spraying task. This will be explored in the following discussion/analysis section.

6. Discussion/Analysis

In this section, the results from the case study ergonomic analysis will be analyzed and discussed. This discussion will include analyzing the results, and then exploring how a partially automated solution would change the results. Finally, lessons learned from this the results of the case study will be discussed.

i. Areas of concern from the results of the classification tool

Based on the results from the full ergonomic analysis, the following areas proved to be the biggest causes for the unsafe ergonomics of the task (R1 ranking): (1) environmental safety, (2) wrist, (3) humidity, clothing, and metabolic rate (heat stress), (4) the lower back posture, (5) hands and wrists-grip, (6) hands and wrists-vibration, and (7) neck posture. These areas should be what is focused on when designing an alternative to improve the ergonomics of this industrial spraying task. For example, because bending the neck and lower back for much of the work day poses great ergonomic risks to workers, solutions should require workers to bend their backs and necks for much less of the day, which would result these measures being classified in the no risk category.

ii. Using the ergonomic analysis results to drive automation design decisions

Upon deciding to improve the ergonomics of this task with a partially automated solution, where robots clean the actual parts, engineers can use the results of the initial ergonomic analysis to drive some of the design decisions. For example, the environmental hazards were a hazard originally, so engineers should design the robotic work cell with extra attention to environmental hazards such as slippery surfaces, uneven surfaces, and ample warning signs, along with the robotic work cell safety features, such as an interlocking barrier around the robot. Secondly, to address the area of risk to the wrist, engineers should ensure that operators do not have to hold or manipulate controls or parts at awkward wrist angles. For example, if engineers required workers to hold a certain lever or part at an awkward wrist position, workers could still be at risk for wrist problems, even though they are not holding the heavy spraying wand anymore. Regarding postures, engineers should pay special attention to all postures that were classified as hazards in the original ergonomic assessment, as well as new, relevant postures that may spring up with the new tasks of the workers. For example, although workers will not be bending their backs as much to inspect parts, engineers should ensure workers are not required to bend over to routinely pull levers or perform their job tasks, when supervising the robots, which will be cleaning the actual parts. Finally, regarding heat stress, engineers should ensure that the worker's environment and metabolic rate are cohesive to the worker, to ensure the heat stress risk is mitigated. One potentially unforeseen benefit of the ergonomic analysis methodology is the exposure to and knowledge of the critical ergonomic factors, which should be taken into consideration, when designing new tasks for workers. Although there are other ergonomic factors (not included in my methodology) that should be considered when designing a supervisory control task, keeping four measures in mind when designing the workers' new tasks and the robotic work cell, will greatly improve workers' ergonomics.

iii. A potential solution: collaborative path planning, semi-automated work cell

One potential solution to greatly improve the ergonomics of this industrial spraying task is to partially automate is via collaborative path planning. Collaborative path planning is a way of using robotic algorithms to generate a path to follow after gathering a point cloud of data. So, for example, in this partially automated solution to the industrial spraying operation in the case study, the algorithm and robot arm would automatically plan and execute a path to clean parts, and perform the actual spraying of the task. The algorithm and robot arm would generate a path to follow to clean the parts, from a point cloud of the parts, obtained from scanning the parts with professional scanners. The professional scanners can be seen in Figure 22, as the black cameras on the walls inside of the work cell. In this solution, the operator would now be sitting in a climate controlled cell, observing and supervising the task to ensure the robot and algorithm are working properly. An example of the climate controlled observation cell is shown as the area next to the steps, shown on the left side of Figure 22. To be able to reach all of the parts, the parts would be placed on a turn table, which turns the parts when the robot arm needs to reach specific areas. A potential cell layout is shown below in Figure 22.

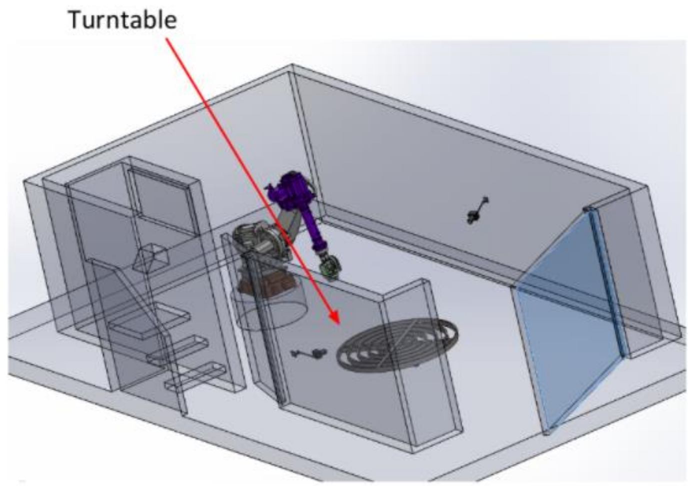


Figure 22: Potential Collaborative Path Planning solution work cell

a. Workers' new job tasks

Now, because the robot arm now automatically generates a path to clean the parts and cleans the parts, the worker has a monitoring role, often called a supervisory role. Table 7 shows the worker's job duties before and after this collaborative path planning solution to improve worker ergonomics. Basically, the worker is taken out of holding the heavy, vibrating sprayer for most of the day, to supervising a robot, while it performs the spraying task. This drastically improves the physical ergonomics of this task, as will be discussed in the next subsection.

	Before partial automation	**After partial automation**
Worker's job duties	(1) Moving parts, (2) inspecting parts, (3) gathering supplies, (4) spraying parts	(1) Supervising the robots, which are doing the spraying, (2) modifying the robot's path as needed, (3) addressing any errors made by the robot

Table 7: Worker's job duties before and after the collaborative path planning partial automated solution to the case study task

b. Evaluation of the new, semi-automated work-cell

Based on the workers' new job duties in this partially automated solution, the ergonomic analysis will be reassessed to see if the scores will improve, as desired. Note, that the reassessments are on the new, hypothetical role of the workers in this new, partially automated industrial spraying operation. Figure 23 shows the results of the ergonomic analysis performed on the partially automated work cell solution. As shown in Figure 23, three (job strain index, Washington State posture screening tool, and the heat stress tool) out of the four measures will almost certainly be classified in the no risk category (N), instead of the hazard category (H). This is because if the worker does not have to hold the sprayer, bend over to spray parts, and move parts for most of their day, the posture and wrist risks will disappear. In addition, because workers will no longer be required to wear hazmat suits in this partially automated example solution, the heat stress risk will disappear as well. It is uncertain how the OSHA recordable injuries and illnesses rate would change, when introducing this partially automated solution, because, although workers will be exposed to less previously encountered environmental hazards, robots bring their own hazards with them. Thus, it is uncertain whether or not this solution would actually significantly decrease environmental hazards. However, since fatigue makes people more at risk to making poor decisions, which can cause environmental injuries, it is likely that the OSHA incidence rate will decrease to the caution area. For example, one of the recordable OSHA incidents was a pulled back. Thus, if workers are not taxed all day from performing the rough spraying work, they will be less likely to pull muscles. For the purposes of this reevaluation of the ergonomic analysis, I will assume that the OSHA incidence rate will move from the hazard to the caution classification. The final combination of scores for the new partially automated solution is CNNN. Thus, from the EMIT model, this elicits a final score of R4. Therefore, the partially automated collaborative path planning solution would greatly improve the overall ergonomics of this particular industrial spraying task.

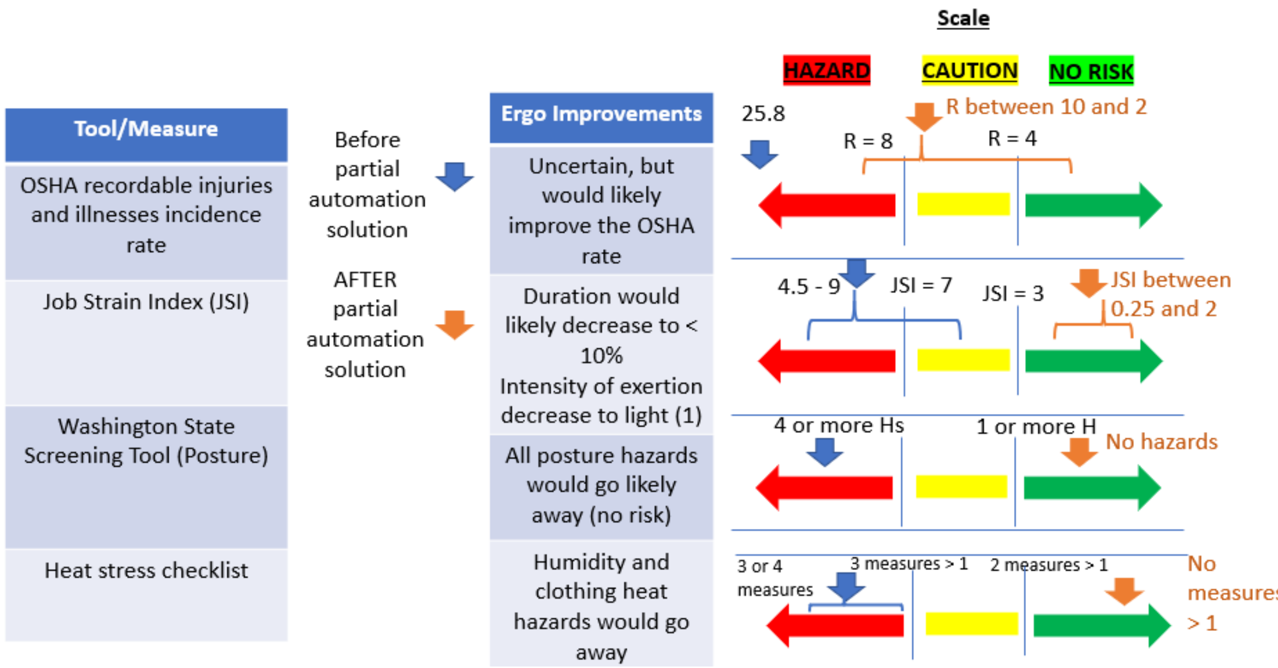


Figure 23: Overall results of the ergonomic analysis before and after the partially automated solution

c. Justification for automation

Overall, the resulting score of R4 from the ergonomic evaluation of the partially automated solution shows that the ergonomics for workers drastically improved from implementing this solution with automation. Thus, this provides a justification for automation from an ergonomics perspective. Although other factors will likely still be considered when automating, such as the financial return on investment and productivity, this ergonomic measure is also important in justifying automation. Although improvements in safety can, to some degree, be quantified in dollars, protecting employees should be a top priority for companies.

7. Conclusions and future work

This research accomplished the initial goals of the analysis, namely creating a tool to comprehensively evaluate the ergonomics of industrial spraying tasks, using the tool to assess a task before and after implementing a potential partial automated solution, and using these results to justify a solution involving automation. The overall conclusions from this research are as follows:

1. Industrial spraying tasks can be comprehensively evaluated, and the tool developed from this research can be used by people without ergonomics backgrounds to evaluate the ergonomics of any industrial spraying task.
2. The ergonomic methodology derived from this research can be used to effectively improve the ergonomics of an industrial spraying task by helping to justify automated (or partially automated) solutions and make design decisions regarding new environments and work tasks for workers.

While this area of research focused in on one area that commonly results in ergonomic injuries, industrial spraying operations, this type of research can and should be expanded to include a variety of other dull, dangerous, and dirty activities, which are excellent candidates for automation. If this research was expanded to apply to more types of tasks, more and more companies and groups would be able to make better, more informed decisions regarding automation and better protecting their employees.

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9. Appendix

Job Strain Index Measure Tables [14]

1. Intensity of Exertion

An estimate of the strength required to perform the task one time. Guidelines for assigning a rating criterion are presented in the following table.

Rating Criterion	% MS[A]	Borg Scale [B]	Perceived Effort
Light	<10%	<=2	barely noticeable or relaxed effort
Somewhat Hard	10%-29%	3	noticeable or definite effort
Hard	30%-49%	4-5	obvious effort; unchanged facial expression
Very Hard	50%-79%	6-7	substantial effort; changes facial expression
Near Maximal	>=80%	>7	uses shoulder or trunk to generate force

[A]Percentage of maximal strength

[B]Compared to the Borg CR-10 scale[78]

2. Duration of Exertion

Duration of Exertion is calculated by measuring the duration of all exertions during an observation period, then dividing the measured duration of exertion by the total observation time and multiplying by 100.

$$\% \text{ Duration of Exertion} = \frac{100 \times \text{duration of all exertions (sec)}}{\text{total observation time (sec)}}$$

3. Efforts per Minute

Efforts per Minute are measured by counting the number of exertions that occur during an observation period, then dividing the number of exertions by the duration of the observation period, measured in minutes.

Efforts per Minute= $\frac{\text{number of exertions}}{\text{total observation time (min)}}$

4. Hand/Wrist Posture

Hand/Wrist Posture is an estimate of the position of the hand or wrist relative to neutral position. Guidelines for assigning a rating criterion are presented in the following table.

Rating Criterion	Wrist Extension[A]	Wrist Flexion[A]	Ulnar Deviation[A]	Perceived Posture
Very Good	0°-10°	0°-5°	0°-10°	perfectly neutral
Good	11°-25°	6°-15°	11°-15°	near neutral
Fair	26°-40°	16°-30°	16°-20°	nonneutral
Bad	41°-55°	31°-50°	21°-25°	marked deviation
Very Bad	>60°	>50°	>25°	near extreme

[A] From derived from data.

5. Speed of Work

Speed of Work is an estimate of how fast the worker is working. Guidelines for assigning a rating criterion are presented in the following table.

Rating Criterion	Compared to MTM-1[A]	Perceived Speed
Very Slow	<=80%	extremely relaxed pace
Slow	81-90%	"taking one's own time"
Fair	91-100%	"normal" speed of motion
Fast	101-115%	rushed, but able to keep up
Very Fast	>115%	rushed and barely or unable to keep up

[A]The observed pace is divided by MTM-1's predicted pace and expressed as a percentage of predicted.

6. Duration of Task per Day

Duration of Task per Day is either measured or obtained from plant personnel.

Job Strain Index

Rating	Intensity of Exertion (IE)	Duration of Exertion (DE)	Efforts/ Minute (EM)	Hand/Wrist Posture (HWP)	Speed of Work (SW)	Duration per Day (DD)
1	Light (1)	<10% (0.5)	<4 (0.5)	Very good (1)	Very slow (1)	<1 (.25)
2	Somewhat hard (3)	10-29% (1)	4-8 (1)	Good (1)	Slow (1)	1-2 (.5)
3	Hard (6)	30-49% (1.5)	9-14 (1.5)	Fair (1.5)	Fair (1)	2-4 (.75)
4	Very hard (9)	50-79% (2)	15-19 (2)	Bad (2)	Fast (1.5)	4-8 (1)
5	Near maximal (13)	80-100% (3)	>=20 (3)	Very bad (3)	Very fast (2)	>=8 (1.5)

JSI = IE x DE x EM x HWP x SW x DD

Heat Stress Checklist Tables [16]

Air Temperature

What is air temperature and what should you look out for?

- Air temperature is described as the temperature of the air surrounding an employee.
- Consider the air temperature surrounding the employee and how you would describe it.

Subjective description of air temperature	Score	Tick
• Cool	-1	
• Neutral	0	
• Slightly warm	1	
• Warm	2	
• Hot	3	
• Very hot	4	
	Don't Know	

Radiant Temperature

What causes radiant temperature and what should you look out for?

- Thermal radiation is the heat that radiates from a heat source and will be present if there are heat sources in an environment.
- Examples include: the sun, electric fires; furnaces; ovens; kiln walls; cookers; dryers; hot surfaces & machinery, exothermic chemical reactions, deep mine tunnel walls; molten metals, etc.
- Observe the surroundings and identify heat sources. Consider how close your employees are to these heat sources. Do they need to wear protective clothing to prevent burns etc?

Subjective description of radiant temperature	Score	Tick
• Objects colder than the surrounding air are near to worker.	-1	
• There are no heat sources in the environment	0	
• A heat source is present but the employees are not in close proximity to it. • The heat source surface is warm to touch and there is no risk of contact burns.	1	
• The heat source surface is hot to touch. • Employees feel hot when they stand near the heat source.	2	
• The heat source surface is very hot to the touch and may burn the skin. • Employees cannot work in close proximity to the heat source for more than 10 minutes without wearing PPE.	3	
• Contact with the heat source will cause burning. • Employees cannot work in close proximity to the heat source for more than 5 minutes without wearing PPE.	5	
• Workers are not permitted to work in the environment without PPE to protect them from the radiant heat in that environment.	6	
Don't Know		

Air Velocity

Air velocity explained

- Air velocity is the speed of air moving across an employee and may affect the employee if it is not cooler than the environment.
- To help you, four categories of air velocity are provided. They are **Still, Low, Moderate** and **High**
    1. **Still** air, is where there is no noticeable flow of air;
    2. **Low** air speed, is when you can just feel air movement on exposed flesh;
    3. **Moderate** air speed, is when you can feel air movement (e.g. a light breeze) on exposed flesh;
    4. **High** air speed, may be similar to the air speed on a windy day, or at or near fans or other machines or equipment that generate air movement.
- Things to look out for are wind sources; the presence of fans to reduce the temperature (e.g. during specialist maintenance work?); employees feeling hot or warm air blowing on any exposed skin or is the moving air cooler or warmer than the ambient air temperature.

Subjective description of air velocity	Score	Tick
• Cold air at a high speed (e.g. employees standing in front of an air conditioning unit).	-3	
• Cold air at a moderate speed, or • Cool air at a high speed.	-2	
• Cold air and low air speed, or • Cool air at a moderate air speed	-1	
• Still air in a neutral environment	0	
• Warm air and low air speed.	1	
• Still air in a warm environment	2	
• Still air in a hot environment.	3	
• Warm air at a moderate air speed, or • Still air in a very hot environment, or • Hot air and moderate air speed.	4	
• Very hot air at a high speed	5	
Don't Know		

Humidity

Humidity explained		
• When water is heated and evaporates into the air this provides the environments humidity. High humidity environments contain a lot of water vapour and this is important as it reduces the ability of sweat to evaporate from the skin which is the main means by which your employees lose heat. • When **vapour impermeable PPE is worn**, sweat cannot evaporate and increases the humidity inside the PPE. If an employee is wearing this sort of PPE (e.g. asbestos, chemical protection suits etc) the humidity within the microclimate of the garment may be high. • Humidity is very difficult to estimate. Profuse sweating may be an indication of high humidity, but it may also be an indication of a high physical activity. • Things to looks out for are is the environment susceptible to outdoor conditions, especially in summer? Are there any dryers or other machines producing steam? Do workers complain about the humidity? Are they wearing vapour impermeable PPE?		
Subjective description of air velocity	**Score**	**Tick**
• No humidity. Air is dry, with no drying processes or other mechanisms for increasing the humidity in the workplace.	**0**	
• Humidity seems to be somewhere between very humid and very dry.	**2**	
• Air is very humid. Examples may be near drying machines, laundry machines, chemical processes where steam is given off.	**5**	
• Vapour impermeable PPE is worn	**6**	
Don't know		

Work Rate

Work rate explained

A, knowledge of the work or metabolic rate, is important when conducting a heat stress risk assessment. The more physical work performed, the more heat produced and the more heat that needs to be lost to prevent overheating.

Observe your employees, note their movements, posture, speed, effort, weight of materials they handle, parts of their bodies responsible for their movement etc? Review your manual handling assessment for information of the components of the task.

Five categories of metabolic rate are described:

1. **Resting,**
2. **Low,**
3. **Moderate,**
4. **High**
5. **Very High.**

Subjective descriptions of work rate	**Score**	**Tick**
Resting • Employee is resting as part of a work/rest schedule or is awaiting instructions etc.	**-2**	
Low • Sitting or standing to control machines • Light hand work (writing, drafting, sewing, bookkeeping, drafting etc). • Hand and arm work (small bench work, using tools such as table saws; drills, inspecting, assembling or sorting light materials, operating control panels, turning low torque hand wheels, very light assembly operating etc). • Standing with light work at machine or bench while using mostly arms (drill press, milling machine, coil taping, small armature winding, machine with light power tools, inspecting or monitoring hot processes). • Arm and leg work (driving a car, operating foot pedals or switches). • Walking in easily accessible areas (can walk upright). • Lifting 4.5 kg loads for fewer than 8 lifts/min; 11 kg few than 4 lifts/min	**0**	
Moderate • Hand and arm work (mailing filing) • Arm and leg work (off road operations of trucks, tractors and construction equipment). • Arm and trunk work (operating air hammer, tractor assembly, cleaning or clearing light debris spillage, plastering, heavy welding, scrubbing while standing up, intermittently handling heavy objects, weeding, hoeing, picking fruit and vegetables). • Carrying, lifting, pulling and pushing light loads (lightweight carts and wheelbarrows); • Operating heavy controls (e.g. opening valves); • Walking in congested areas (limited headroom), walking 2 to 3 mph. • Lifting: 4.5 kg fewer than 10 lifts/min, 11 kg fewer than 6 lifts/mins	**2**	

Clothing

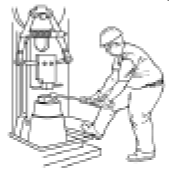
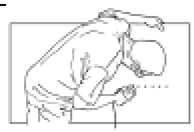
Clothing explained

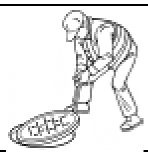
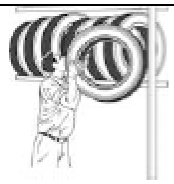
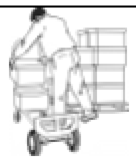
- Clothing interferes with our ability to lose heat to the environment. Where heat stress is a risk eg where workers may be wearing PPE, even if the environment is not considered warm or hot. It is important to identify whether the clothing the employee is wearing may contribute to the risk of heat stress.
- It is impossible to list or describe all the clothing that may be worn in industry so only general descriptions of clothing are provided.
- Observe the employee and select the clothing type that best represents what is worn in that workplace. Where employers wear or remove clothing depending on the job or task, it may be necessary to conduct a quantitative heat stress risk assessment.
- Additional information may be obtained by contacting the manufacturer or supplier of the PPE for further advice.

Subjective descriptions of clothing	Score	Tick
• Shorts and a T-shirt. No protective or work clothing worn	-1	
• Light work clothing	0	
• Cotton coverall, jacket	2	
• Winter work clothing, double cloth coveralls, water barrier materials.	3	
• Light weight vapour barrier suits	5	
• Fully enclosed suit with hood and gloves.	6	
	Don't know	

WISHA Posture Screening tool tables [15]

WISHA Caution/Hazard Checklist Modified 2

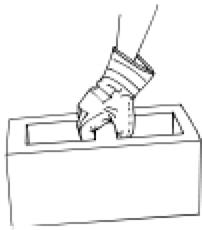
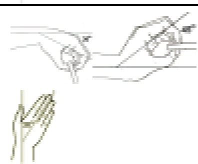
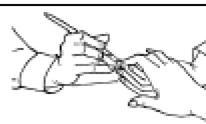
Low Back Posture		Overall: None	Caution	Hazard
Working with the back bent forward more than 30° (without support or the ability to vary posture)		More than 2 hours total per day.		Caution ❑
		More than 4 hours total per day		Hazard ❑
Working with the back bent forward more than 45° (without support or the ability to vary posture)		More than 1 hour total per day.		Caution ❑
		More than 2 hours total per day		Hazard ❑

Weight/Force				
Lifting object weighing more than 75 pounds		One or more times per day		Hazard ❑
Lifting object weighing more than 55 pounds		More than 10 times per day		Caution ❑
		More than 20 times per day		Hazard ❑
Lifting objects weighing above the shoulders, below the knees or at arms length more than 25 times per day		More than 10 pounds		Caution ❑
		More than 20 pounds		Hazard ❑
Lifting objects weighing more than 10 pounds if done more than twice per minute		More than 2 hours total per day		Caution ❑
		More than 4 hours total per day		Hazard ❑

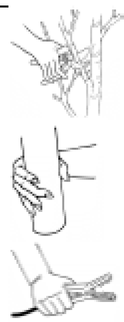
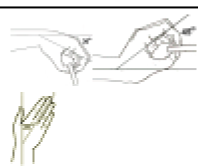
Hands and Wrists

Overall: None Caution Hazard

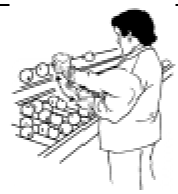
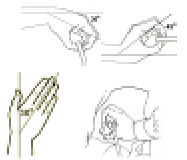
Pinch Grip

Pinching an unsupported object(s) weighing 2 or more pounds per hand, or pinching with a force of 4 or more pounds per hand		More than 2 hours total per day.	Caution ☐
		More than 4 hours total per day	Hazard ☐
Pinching Caution plus wrist deviation		More than 3 hours total per day	Hazard ☐
Pinching Caution plus highly repetitive motion		More than 3 hours total per day	Hazard ☐

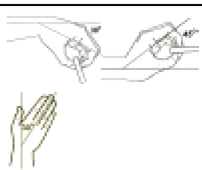
Grasp Grip

Gripping an unsupported objects(s) weighing 10 or more pounds per hand, or gripping with a force of 10 or more pounds per hand (comparable to clamping light duty automotive jumper cables)		More than 2 hours total per day.	Caution ☐
		More than 4 hours total per day	Hazard ☐
Gripping Caution plus wrist deviation		More than 3 hours total per day	Hazard ☐
Gripping Caution plus highly repetitive motion		More than 3 hours total per day	Hazard ☐

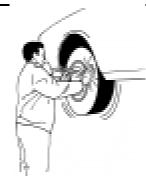
Repetitive Motion of Hands

Repeating the same motion with the elbows, wrists, or hands (excluding keying activities) with little or no variation every few seconds		More than 2 hours total per day.	Caution ❑
		More than 6 hours total per day	Hazard ❑
Repetition Caution plus high, forceful exertions with the hand(s) and wrist deviation		More than 2 hours total per day	Hazard ❑

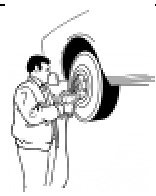
Keying

Intensive keying		More than 4 hours per day	Caution ❑
		More than 7 hours per day	Hazard ❑
Intensive keying with wrist deviations		More than 4 hours per day	Hazard ❑

Hand Impacts

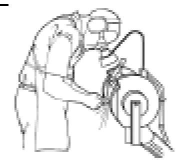
Using the hand (heel/base of palm) as a hammer more than 2 hours per day		More than 10 times per hour	Caution ☐
		More than 1 time per minute	Hazard ☐

Hand-Arm Vibration

Using grinders, sanders, jigsaws or other hand tools that typically have moderate vibration levels		More than 2 hours per day	Caution ☐
		More than 4 hours per day	Hazard ☐
Using impact wrenches, carpet strippers, chain saws, percussive tools (jack hammers, scalers, riveting or chipping hammers) or other tools that typically have high vibration levels		More than 30 minutes per day	Caution ☐
		More than 1 hour per day	Hazard ☐

Neck and Shoulder Overall: None Caution Hazard

Neck Posture

Working with the neck bent more than 30 degrees (without support and without the ability to vary posture)		More than 2 hours total per day.		Caution ❑
Working with the neck bent more than 45° (without support or the ability to vary posture)		More than 2 hours total per day.		Caution ❑
		More than 4 hours total per day		Hazard ❑

Shoulder Posture

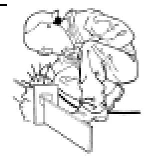
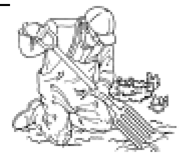
Working with the hand(s) above the head, or the elbows above the shoulders		More than 2 hours total per day.		Caution ❑
		More than 4 hours total per day		Hazard ❑
Repeatedly raising the hand(s) above the head, or the elbow(s) above the shoulder(s) more than once per minute		More than 2 hours total per day.		Caution ❑
		More than 4 hours total per day		Hazard ❑

Repetitive Motion of Shoulder

Repeating the same motion with the neck or shoulders with little or no variation every few seconds		More than 2 hours total per day.		Caution ❑
		More than 6 hours total per day		Hazard ❑

Knee **Overall: None Caution Hazard**

Posture

Squatting		More than 2 hours total per day.		Caution ☐
		More than 4 hours total per day		Hazard ☐
Kneeling		More than 2 hours total per day.		Caution ☐
		More than 4 hours total per day		Hazard ☐

Knee Impacts

Using the knee as a hammer more than 2 hours per day		More than 10 times per hour		Caution ☐
		More than 1 time per minute		Hazard ☐

EMIT model tables

Legend 1		
H	Hazard	
C	Caution	
N	No Risk	

Legend 2			Criteria
R1		Dangerous	2 or more H levels, or 4 caution levels
R2		Risky	1 H level, or 3 caution levels
R3		Moderate risk	2 caution levels
R4		Safe	1 or fewer caution levels

OSHA Rate	Job Strain	VISHA Posture	Heat stress	Combination of	Risk Level
H	H	H	H	HHHH	R1
			C	HHHC	R1
			N	HHHN	R1
		C	H	HHCH	R1
			C	HHCC	R1
			N	HHCN	R1
		N	H	HHNH	R1
			C	HHNC	R1
			N	HHNN	R1
	C	H	H	HCHH	R1
			C	HCHC	R1
			N	HCHN	R1
		C	H	HCCH	R1
			C	HCCC	R2
			N	HCCN	R2
		N	H	HCNH	R1
			C	HCNC	R2
			N	HCNN	R2
	N	H	H	HNHH	R1
			C	HNHC	R1
			N	HNHN	R1
		C	H	HNCH	R1
			C	HNCC	R2
			N	HNCN	R2
		N	H	HNNH	R1
			C	HNNC	R2
			N	HNNN	R2

C	H	H	H	CHHH	R1
			C	CHHC	R1
			N	CHHN	R1
		C	H	CHCH	R1
			C	CHCC	R2
			N	CHCN	R2
		N	H	CHNH	R1
			C	CHNC	R2
			N	CHNN	R2
	C	H	H	CCHH	R1
			C	CCHC	R2
			N	CCHN	R2
		C	H	CCCH	R2
			C	CCCC	R1
			N	CCCN	R2
		N	H	CCNH	R2
			C	CCNC	R2
			N	CCNN	R3
	N	H	H	CNHH	R1
			C	CNHC	R2
			N	CNHN	R2
		C	H	CNCH	R2
			C	CNCC	R2
			N	CNCN	R3
		N	H	CNNH	R2
			C	CNNC	R3
			N	CNNN	R4

N	H	H	H	NHHH	R1
			C	NHHC	R1
			N	NHHN	R1
		C	H	NHCH	R1
			C	NHCC	R2
			N	NHCN	R2
		N	H	NHNH	R1
			C	NHNC	R2
			N	NHNN	R2
	C	H	H	NCHH	R1
			C	NCHC	R2
			N	NCHN	R2
		C	H	NCCH	R2
			C	NCCC	R2
			N	NCCN	R3
		N	H	NCNH	R2
			C	NCNC	R3
			N	NCNN	R4
	N	H	H	NNHH	R1
			C	NNHC	R2
			N	NNHN	R2
		C	H	NNCH	R2
			C	NNCC	R3
			N	NNCN	R4
		N	H	NNNH	R2
			C	NNNC	R4
			N	NNNN	R4

Raw Time Study and Washington State Screening Tool results

High Temperature Spraying Activity Time Study Data

Start time	Stop Time
12:55 PM	1:05 PM
1:05 PM	1:22 PM
1:22 PM	1:24 PM
1:24 PM	1:31 PM
1:31 PM	1:37 PM
1:37 PM	1:46 PM
1:46 PM	1:48 PM
1:48 PM	1:52 PM
1:52 PM	1:56 PM
1:56 PM	1:57 PM
1:57 PM	2:00 PM

	Total % of time spraying	63.5%
Duration of Exertion	Total % of time spraying (incorporating both time studies)	67.5%
Efforts per min		0.07
Duration per day		5.9

Activity Details	**Time with back bent more then <u>45 degrees</u> without support (mins)**	**Total Time observed in the random sample (mins)**	
Inspecting and moving parts	2.60	5	
Spraying	1.60	3	
Getting Supplies and Spraying	3.93	4	
Spraying and Inspecting	3.67	6	
	11.80	18	**Totals**
	Total % of time spent with back bent more than 45 degrees	65.6%	
	Note- when the lower back was bent over > 45 degrees, the neck was also bent over greater than 45 degrees		

High Pressure Spraying Activity Time Study Data

Activity	Duration (mins)	Start time	Stop Time	
Inspecting Parts	4	2:47 PM	2:51 PM	
Spraying	20	2:51 PM	3:11 PM	
Total	24			
			Total % of time Spraying	83.3%

Sample Number	Activity Details	Time with back bent more then 30 degrees without support (mins)	Total Time observed in the random sample (mins)
1	Inspecting and moving parts	1.40	6
2	Getting Supplies and Spraying	0.00	6
3	Spraying	2.22	6
		3.62	18
		Total % of time spent with back bent more than 30 degrees	20.1%

Actual Raw WISHA screening tool results

Productive hours in a workday (hrs):	8.75	Legends:	Caution	(yellow)
			Hazard	(red)

Area	Description	% of time in this posture	Time per day in this posture (hrs)
Lower Back	Working with the back bent forward more than 30° (without support or the ability to vary posture)	20.1%	0.35
Lower Back	Working with the back bent forward more than 45° (without support or the ability to vary posture)	65.6%	4.59
Weight/Force	Lifting object weighing more than 75 pounds	N/A	
Weight/Force	Lifting object weighing more than 55 pounds	N/A	
Weight/Force	Lifting objects weighing above the shoulders, below the knees or at arms length more than 25 times per day	N/A	
Weight/Force	Lifting objects weighing more than 10 pounds if done more than twice per minute	N/A	

Area	Description	% of time in this posture	Time per day in this post (hrs)
Hands and Wrists- Pinch Grip	Pinching an unsupported object(s) weighing 2 or more pounds per hand, or pinching with a force of 4 or more pounds per hand	N/A	
	Pinching Caution plus wrist deviation	N/A	
	Pinching Caution plus highly repetitive motion	N/A	
Hands and Wrists- Grasp Grip	Gripping an unsupported objects(s) weighing 10 or more pounds per hand, or gripping with a force of 10 or more pounds per hand (comparable to clamping light duty automotive jumper	N/A	
	Gripping Caution plus wrist deviation	67.5%	5.9
	Gripping Caution plus highly repetitive motion	N/A	

Area	Description	% of time in this posture	Time per day in this post (hrs)
Repetitive Motion of Hands	Repeating the same motion with the elbows, wrists, or hands (excluding keying activities) with little or no variation every few seconds	N/A	
	Repetition Caution plus high, forceful exertions with the hand(s) and wrist deviation	N/A	
Keying	Intensive keying	N/A	
	Intensive keying with wrist deviations	N/A	
Hand Impacts	Using the hand (heel/base of palm) as a hammer more than	N/A	
Hand-Arm Vibration	Using grinders, sanders, jigsaws or other hand tools that typically have moderate vibration levels	67.5%	5.9
	Using impact wrenches, carpet strippers, chain saws, percussive tools (jack hammers, scalers, riveting or chipping hammers) or other tools that typically have high vibration levels	N/A	

Area	Description	% of time in t[illegible] posture	Time per day in t[illegible] posture (hrs)
Neck and Shoulder- Neck Posture	Working with the neck bent more than 30 degrees (without support and without the ability to vary	20.1%	0.4
	Working with the neck bent more than 45° (without support or	65.6%	4.6
Neck and Shoulder- Shoulder Posture	Working with the hand(s) above the head, or the elbows above the shoulders	N/A	
	Repeatedly raising the hand(s) above the head, or the elbow(s) above the shoulder(s)	N/A	
Neck and Shoulder- Repetitive Motion of Shoulder	Repeating the same motion with the neck or shoulders with little or no variation every	N/A	
Knee Posture	Squatting	N/A	
	Kneeling	N/A	
Knee Impacts	Using the knee as a hammer more than 2 hours per day	N/A	