Development of a Scoring Methodology for Ergonomic Risk Assessment in the Workplace

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Abstract

This paper presents a scoring methodology for assessing ergonomic risks. The proposed methodology consists of three main phases: (1) identifying ergonomic risk factors, (2) defining ergonomic risk scores, and (3) calculating and prioritizing ergonomic risks. In the first phase, the main factors that can cause ergonomic risks are identified based on process and task mapping techniques. In the second phase, score levels are defined for each ergonomic risk factor based on the ergonomic standards developed by different organizations and researchers. In the third phase, current ergonomic risks in the workplace are calculated and prioritized so that the high risks can be mitigated by implementing proper action plans. The proposed methodology helps decision makers evaluate and assess ergonomic risks in an easy way. A case study from a manufacturing environment is presented. Results showed that the proposed method can be used as a basis for identifying ergonomic risks and developing effective mitigation and control plans for these risks.

Keywords
Ergonomic assessment, risk scoring, risk prioritization, manufacturing.

1. Introduction
Ergonomics is defined as the study of work to design jobs, equipment, and work tasks to fit human physical characteristics. It focuses on the work environment to eliminate all potential body-related and mental stresses. Some of the main benefits of ergonomics include safer jobs and fewer injuries, better productivity and efficiency, and improved quality. The aspects of a particular job or task that impose effects on the worker or employee are considered as ergonomic risk factors. Most common ergonomic risks are repetition, awkward body posture, cold/hot temperature, contact stress, illumination, force, static postures, and vibration. Each year, many workers are killed or injured on the job in the United States and other countries. According to the Occupational Safety and Health Association (OSHA), almost 3.1 million nonfatal workplace injuries and illnesses were reported in 2010 among private industry employers in the United States (incident rate: 3.5 cases per 100 equivalent full-time workers). Occupational ergonomic risks exist in any industry, service or manufacturing. The risk can be defined as the possibility that risk factors in the work environment will occur and affect employees and organization. The risk consists of three main events: initiating events or risk factors, middle or central risk event, and resulting events or the risk impact. Initiating events are the root causes of the risk which, if occurred, could cause the central risk event to happen. Middle event is the central risk event that, if occurred, could cause negative impact on people, organization, and/or environment. Adequate protection of workers against occupational ergonomics risks is a matter of considerable concern to many organizations. Effective management of these risks in the work environment is important for the safety and health of the operators, productivity, and worker satisfaction. Ergonomic risk assessment for a company can be constructed by considering the risks in each area and then combining the risks. Risk assessment can be enhanced by using simulation and modeling techniques

such as digital human modeling where the real work environment is modeled as a combination of virtual environment and digital humans. Real physical work is imitated by tasks performed by digital humans in the virtual environments. Different ergonomic risk measurement approaches such as Rapid Upper Limb Assessment (RULA) and Rapid Entire Body Assessment (REBA) are used for the assessment. Recommendations for improvement include new equipment, administrative controls, and documented work procedures. Table 1 shows the main categories for ergonomic risks and their related factors, standards, and measurement tools.

In this study, a scoring methodology for assessing ergonomic risks is proposed. The workplace is divided into areas, the areas into processes, and the processes into tasks. The tasks' risks in each area are aggregated to calculate the area risk scores. Once the risks are identified and prioritized, risk reduction strategies are proposed and implemented to mitigate the risks. The proposed scoring system helps the decision makers assess the ergonomic risks in an easy way. The rest of this paper is organized as follows: Section 2 provides a review of the literature related to ergonomic risks assessment. Section 3 discusses the proposed scoring system for ergonomic risk assessment. In Section 4, application of the proposed framework in a real manufacturing is presented. Finally, recommendations and future work extensions are summarized in Section 5.

2. Relevant Literature

Ergonomic risk that an employee faces in the workplace is a function of the hazards present and the exposure level to those hazards. Assessment of ergonomic risks in the workplace must be performed continuously to prevent illness and injuries to employees. Several studies in the literature discussed the assessment and analysis of ergonomic risks in the workplace. A review of ergonomic intervention studies was presented in Westgaard and Winkel (1997). Cheng et *al.* (2013) investigated the prevalence of work-related musculoskeletal disorders in early intervention educators and evaluated the relationship between the work-related disorders and the personal/ergonomic risk factors. Similar studies were conducted in different manufacturing and service industries. For example, Vignais *et al.* (2013) presented a system that permits a real-time ergonomic assessment of manual tasks in an industrial environment. The identification of ergonomic interventions for building installation tasks was discussed in Albers *et al.* (2005). Ergonomic tools such as digital human modeling can be used for assessing the ergonomic risks. An investigation of how ergonomics risks assessments using digital human modeling match real-life assessments was performed by Fritzsche (2010). The investigation was conducted on a car assembly line where two ergonomists evaluated 20 work tasks. Tornstrom *et al.* (2008) discussed a corporate workforce model for ergonomic assessment considering a case study from car industry. A real-time ergonomic feedback system was discussed in Vignais *et al.* (2013). A biomechanical model was developed for the upper body using inertial sensors placed at differet locations on the upper body. A computerized RULA was implemented based on the biomechanical model to assess the ergonomic risks in real-time. Measuring the operational performance and employee well-being was discussed in Hoffmeister (2015). The study introduced a framework for ergonomic climate to support the design and modification of work to maximize both the performance and well-being outcomes. Shikdar *et al.* (2002) developed a software package for ergonomic assessment of manufacturing industry. The developed software can be used as a self-assessment tool to evaluate ergonomic improvement potential of production systems by engineers, managers, and safety professionals. Kaklanis *et al.* (2015) discusses the development of Virtual User Models (VUMs) to assess ergonomic risks for people with disabilities. The authors performed regression analysis to evaluate the variability of the disability parameter.

Other studies discussed the assessment of ergonomic risks in different work environments. For example, Jones and Kumar (2007) performed an assessment of ergonomic risks in sawmill facilities. The study compared the results of different ergonomic risk assessment methods and examine the effect of posture and excretion on the risk assessment methods. Saurin Guimaraes (2008) discussed the assessment of ergonomic risks for suspended scaffolds. The assessment criteria considered in the study included: workers' perceptions of effort, body posture assessment; heart rate elevations, scaffolds' speed and, repetitiveness of movement in the scaffolds' levers. A case study for knowledge-based assessment of working conditions in surgical ward was presented in Bartnicka (2015). Even with the availability of many different ergonomic assessment methods, there is a lack of scoring systems that standardize the scores of the different ergonomic risk factors for easy evaluation and comparison. Furthermore, most of the studies that focus on assessing ergonomic risks in work environment consider only some of the risk factors. This study provides a scoring methodology that considers the main ergonomic risk factors in the workplace. The values of the ergonomic risk factors are converted into a percentage score based on matching the risk values to the standards developed by different organizations and researchers. Furthermore, a case study from a real electronic manufacturing environment is provided to assess the applicability of the proposed scoring methodology.

Table 1: Ergonomic requirements and associated factors

Requirement Category	Ergonomic Factors	Standards (References)	Measurement Method	Unit of Measurement
Environmental conditions	Illumination	OSHA	Light Meter	Foot-Candle, Lux Meter
	Temperature	ACGIH	WBGT Meter	ºC, ºF, K
	Noise	OSHA	Sound-level meter	dBA
Equipment and Tools Characteristics	Hand-Arm Vibration	ACGIH	Human Vibration Analyzer	m/s^2
	Whole Body Vibration	ISO	Human Vibration Analyzer	m/s^2
	Size and Shape	NIOSH	Experts' Judgment	m^3, in^3
	Weight and Weight Distribution	NIOSH	Experts' Judgment, Weight Measure	Kg, lb
Task Physical Requirements	Force	NIOSH	Force models, digital human modeling	N, lb_f
	Repetition	REBA, RULA, OWAS	Manual calculations, digital human modeling	Frequency, qualitative score
	Work postures	REBA, RULA, OWAS	Manual calculations, digital human modeling	Qualitative score
	Duration	REBA, RULA	Manual calculations, digital human modeling	Seconds, minutes, hours
	Energy expenditure	OSHA	Heart-rate monitor, Qualitative Assessment	Kcal/min
Human Physical Characteristics	Weight	Experts' Judgment	Experts' Judgment	kg, lb
	Height	Experts' Judgment	Experts' Judgment	m, ft
	Age	Experts' Judgment	Experts' Judgment	Years
	Gender	Experts' Judgment	Experts' Judgment	M/F
Workplace layout	Work reaches	OSHA	Manual calculations, digital human modeling	m, ft
	Work heights	OSHA	Manual calculations, digital human modeling	m, ft
	Floor surfaces	Experts' Judgment	Experts' Judgment	Qualitative score
	Contact stress	OSHA	Manual calculations	N, lb_f
Work organization	Rest breaks	OSHA	Experts' Judgment	Minutes, hours
	Work rate	Experts' Judgment	Experts' Judgment	Qualitative score
	Task variability	Experts' Judgment	Experts' Judgment	Qualitative score

3. Proposed Scoring System for Ergonomic Assessment

The proposed system for ergonomic assessment consists of three main phases: 1) identifying ergonomic risk factors, 2) defining ergonomic risk scores, and 3) calculating and prioritizing ergonomic risks. In the first phase, the main factors causing ergonomic risks are identified based on process and task mapping techniques. In the second phase, scores are defined for each ergonomic risk factor based on ergonomic standards developed by different organizations and researches. In the third phase, current ergonomic risks in the workplace are calculated and prioritized so that high risks can be mitigated by implementing proper action plans. The following sections discuss the three phases in detail.

3.1 Ergonomic Risk Factors Identification

Process mapping is a technique used to identify all the activities and entities involved in a given process. It provides an opportunity to learn about the process, in a visual representation. Process mapping can be used for ergonomic assessment to identify all the activities and/or work areas that may affect the workers. The workplace is represented by a collection of areas and risks are evaluated for each area. Moreover, ergonomic risk exposures are evaluated per risk type (e.g., noise, posture, vibration, etc.). Different areas in the workplace may present different ergonomic hazards. Operator may work in different areas and hence the number of persons working in the area and among areas should be considered. Risks are also evaluated per task and per process (group of tasks). Figure 1 shows the areas of the workplace. Assessment of ergonomic risks starts with the tasks and the task risks are aggregated to evaluate the process risk. Similarly, processes risks are aggregated to evaluate the area risk. Ergonomic risks are categorized into: noise, illumination, vibration, temperature, workload (energy expenditure), and posture/force risks. To evaluate the areas (or processes) risks, Ergonomic Risk Matrix is used (see Table 2). The total score for areas risks (RS_i) and risk types (RE_j) are calculated as:

$$RS_i = \sum_{j=1}^{m} w_j R_{ij}, \ \mathrm{i} = 1,2,\ldots,\mathrm{n} \quad \ldots\ldots \quad (1)$$

$$RE_j = \sum_{i=1}^{n} w_i R_{ij}, \ \mathrm{j} = 1,2,\ldots,\mathrm{m} \quad \ldots\ldots \quad (2)$$

Number of workers should also be considered and the risks are normalized by the number of operators as follows:

$$\mathrm{R}_{\mathrm{ij}}^{\mathrm{norm}} = \frac{\mathrm{K}_{\mathrm{ij}} * \mathrm{R}_{\mathrm{ij}}}{\sum_{i=1}^{N}\sum_{j=1}^{M} \mathrm{K}_{\mathrm{ij}}}, \quad \ldots\ldots \quad (3)$$

where w_i and w_j are weights assigned to the risks and K_{ij} is the number of operators who can be affected by the risk R_{ij}.

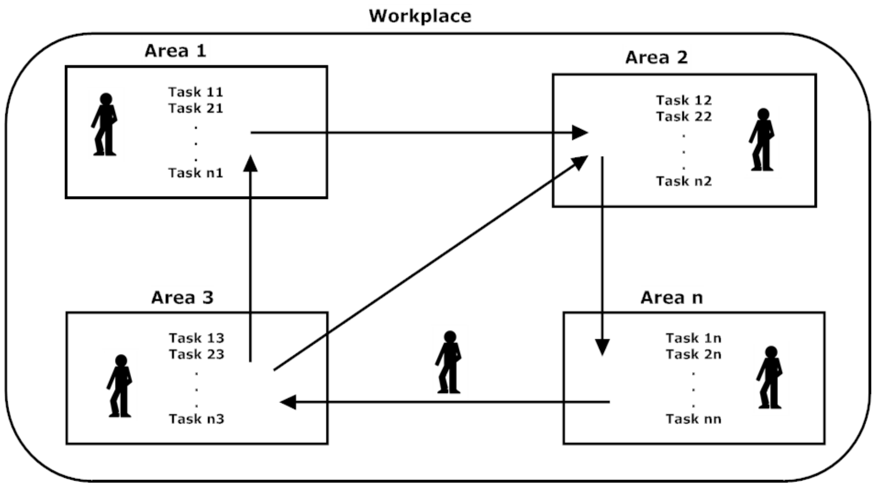

Figure 1. Representing the workplace as a collection of areas

Table 2. Ergonomic Risk Matrix

Workplace Area	Risk 1	Risk 2	Risk 3	. . . . .	Risk m	Area Risk
Area 1	R_{11}	R_{21}	R_{31}	. . . . .	RM_1	RS_1
Area 2	R_{12}	R_{22}	R_{32}	. . . . .	RM_2	RS_2
Area 3	R_{13}	R_{23}	R_{33}	. . . . .	RM_3	RS_3
. . .	. . .	. . .	. . .	. . .	. . .	. . .
Area n	R_{1n}	R_{2n}	R_{3n}		R_{mn}	RS_n
Ergonomic Risk	RE_1	RE_1	RE_1		RE_m	

3.2 Defining Ergonomic Risk Scores

In order to determine if an ergonomic situation represents a risk to the human, a scoring system is required that coverts the measured value of ergonomic factors into a risk score by comparing the measured values to the standards proposed by specialized organizations. The following subsections discuss the scoring levels for each ergonomic risk factor.

3.2.1 Energy Expenditure (EN)

It is important to arrange and design the workspace in a way that reduces the required energy to perform the task or job. Total energy expenditure for a certain task represents the average amount of energy spent to achieve the task for a certain period of time. The required energy for a task is estimated by measuring the energy expenditure in addition to the basal energy which is the energy needed for human body activities including the energy required to maintain body temperature and brain function. Basal energy varies from 40 to 70 percent of the daily total energy expenditure depending on the individual's gender, age, and body size and shape. Physical activities represent a major factor of the daily energy expenditure that human-beings are consuming and it varies and depends on the type and duration of the tasks. Total consumed energy should be equal or less than the intake energy; otherwise, the human being will not be able to function properly and will have physical or social limitations in implementing certain tasks or activities. Estimates of the average total energy expenditure are driven from measurements of individuals; individuals are of the same gender, and similar body size, age, and physical activities grouped to give an average on the total energy expenditure. Energy expenditure can be measured by different ways including oxygen consumption, heart rate, and OSHA standards for energy expenditure. Heart rate monitoring is one of the accredited measures of the total energy expenditure. The total average energy expenditure can be calculated as:

$$E_{job} = E_{basal} + \frac{\sum_{i=1}^{n} E_{task\,i}\, T_{task\,i}}{\sum_{i=1}^{n} T_{task\,i}}, \quad (4)$$

where, E_{job} is the total average energy expenditure rate for a certain job (in Kcal/min). E_{basal} is the metabolic energy required to maintain human's body activities (in Kcal/min). $E_{task\,i}$ is the energy required to perform task *i* (Kcal/min). T_{taski} is the time duration of task i in minutes. The basal energy can be calculated based on the revised Harris-Benedict equations (Rozavand Shizgal, 1984) as:

Basal Energy Expenditure (BBE) for men:
BEE = 88.363 + (13.397 x weight in kg) + (4.799 x height in cm) − (5.677 x age in years)

Basal Energy Expenditure (BBE) for women:
BEE = 447.593 + (9.247 x weight in kg) + (3.098 x height in cm) − (4.330 x age in years)

According to the equations above, for a man weighted 70 kg, 170 cm height and 40 years old, the basal energy expenditure will be 1611.502 kcal/day or 1.119 kcal/min. For woman with the same specifications, basal energy expenditure will be 1448.343 kcal/day or 1.005 kcal/min. 5.33 kcal/min is the acceptable average energy expenditure for 8-hour time duration of a task for men and 4 kcal/min for women according to (Ayabar *et al.*, 2015). Based on this, average energy expenditure range for men and women are rated as shown in Table 3 and Figures 2 and 3.

Table 3. Average Energy Expenditure

Male Energy Expenditure (kcal/min)	Female Energy Expenditure (kcal/min)	Rating of Work	Color Code
≤ 1.5	≤ 2.5	Light Work	Green
> 1.5 and ≤ 4	> 2.5 and ≤ 5.33	Moderate Work	Green
> 4 and ≤ 6.5	> 5.33 and ≤ 7.5	Heavy Work	Yellow
> 6.5 and ≤ 9	> 7.5 and ≤ 10	Very Heavy Work	Brown
> 9	> 10	Extreme Work	Red

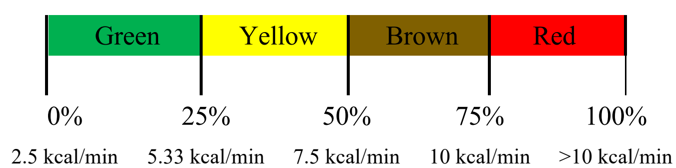

Figure 2. Energy Expenditure scoring for men

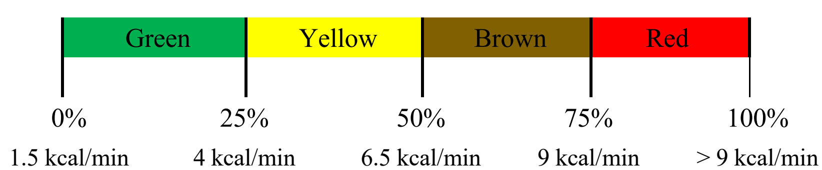

Figure 3. Energy Expenditure scoring for women

Based on the scoring above, we can develop equations for the upper and lower limits of energy expenditure as:

$$EEL = 1.5\,(1 + X) + 2.5\,Y$$
$$EEU = 1.5\,(1 + X) + 2.5\,(1 + Y)$$

where: X = 0 for female and 1 for male; and Y = 0 for green, 1 for yellow, 2 for brown, and 4 for red. EEL is the lower limit and EEU is the upper limit for energy expenditure. The percentage score for the energy expenditure value can be determined as:

$$EE\% = max\left(0, \frac{EE_C - 1.5(1+X)}{10}\right) \times 100\%, \quad (5)$$

where EE_c is the calculated value of the energy expenditure. Any negative values are considered 0%. For example, if the energy expenditure of a given task is 9.5 kcal/min, the percentage score for the task will be: [(9.5 - 1.5 * 1)/10] x 100% = 80% for female and [(9.5 - 1.5 * 2)/10] x 100% = 65% for male.

3.2.2 Noise (NZ)

Noise level in the workplace has a major impact on the person's performance. Exposure to high levels of noise can have many negative effects on individuals and the result can vary from simple physical damage to loss of hearing. According to OSHA, by considering the level of sound, over the work hours, is constant, we can calculate the allowable noise dose for a certain period of time by using the equation:

$$D = 100 \sum_{i=1}^{n} \frac{C_i}{T_i} \quad (6)$$

where D is the noise dose, C_i is the total time of exposure at a specific noise level measured in hours, T_i is the reference duration recommended by OSHA, in consideration to the sound level L. Reference duration (T), recommended by OSHA, under constant sound level (L) can be calculated according to the Equation:

$$T = \frac{8}{2^{(L-90)/5}}, \quad (7)$$

where T is the exposure duration of time to the noise that is allowed and it measured in hours. L is the sound level and measured in dBA. Equation (6) can be rewritten as:

$$D = 12.5 \sum_{i=1}^{n} 2^{(L_i-90)/5} C_i \quad (8)$$

where L is the noise level, T is the exposure time, D is the noise dose OSHA Level is the recommended limits which was set by OSHA. The score levels for noise are shown in Figure 4.The noise score (*NZ%)* is then calculated as:

$$NZ\% = \frac{D \times 25}{33} \times 100\%, \quad (9)$$

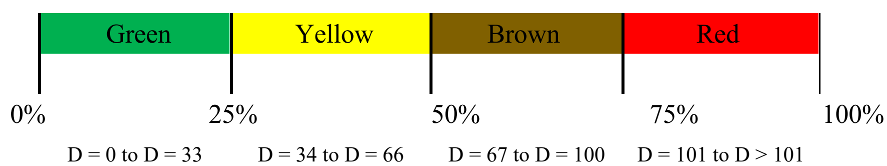

Figure 4. Noise level scores

3.2.3 Vibration

Impact of vibration on human depends on many factors including: (1) type and duration of the task, (2) how long the task will take, (3) how many times per day an individual will use the vibratory tool, (4) position of the vibratory tool and its size and shape, and (5) individual factors: body size, body posture and body tension. Thorough evaluation of exposure to vibration requires measurement and definition of acceleration and direction, frequency and duration of the vibratory tools. Based on its impact, vibration is divided into: (1) Hand-arm vibration (HV), and (2) Whole body vibration (WV). The sensitivity of an individual's hand to vibration depends on the frequency. The frequency level range that would generate the highest sensitivity is in the range of 8-16 Hz, with respect to exposure duration. Threshold Limit Values (TLVs) for vibration exposure to handheld tool have been developed by American Conference of Governmental Industrial Hygienists (ACGIH). Standards for safety frequency range and time duration have been provided in order to reduce hand-arm vibration syndrome. Vibration is measured in units of acceleration, which is m/s^2. Table 4 shows the ratings of hand-arm vibration for an average of 8-hour working period.

Table 4. Hand-arm vibration ratings (adapted from Meada and Shibata, 2008)

Vibration Total Value (m/s^2)	Comfort Level	Color Code
< 0.747	Not uncomfortable	Green
≥ 0.747 and < 1.735	A little uncomfortable	Green
≥ 1.735 and < 3.060	Fairly uncomfortable	Yellow
> 3.060 and < 6.590	Uncomfortable	Brown
≥ 6.590	Extremely uncomfortable	Red

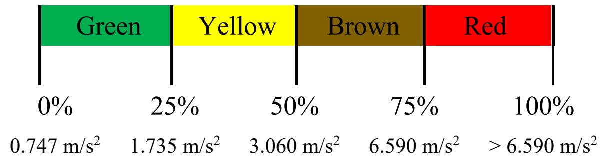

Figure 5. Hand-arm vibration scoring

The HV score can be calculated as:

$$HV\% = max\left(0, min\left(1, \frac{HV - 0.747)}{f}\right)\right) \times 100\%, \ldots\ldots\ldots \quad (10)$$

where $f = 3.952$ if $HV < 1.735$, $f = 3.952$ if $HV < 3.06$, and $f = 3.952$ if $HV < 6.590$

For the whole body vibration, the values will depend upon whether the person is sitting or standing. Tables 5 and 6 show the values for both situations for an average of 8-hour working period. Table 5 is adopted from ISO 2631-1 (1997) and Table 6 is adopted from Oborne and Clarke (1974). The percentage scoring for sitting and standing position are shown in Figures 6 and 7, respectively.

Table 5. Whole body vibration ratings for sitting

Vibration Total Value (m/s^2)	Comfort Level	Color Code
< 0.315	Not uncomfortable	Green
≥ 0.315 and < 0.63	A little uncomfortable	Green
> 0.5 and < 1	Fairly uncomfortable	Yellow
> 0.8 and < 1.6	Uncomfortable	Brown
> 1.25 and < 2.5	Very uncomfortable	Red
> 2	Extremely uncomfortable	Red

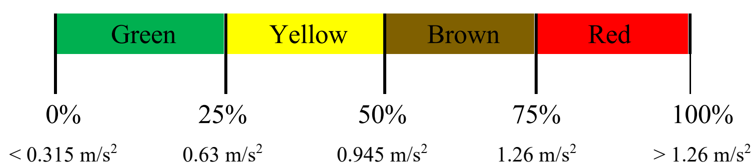

Figure 6: Whole body vibration scoring for sitting

Table 6. Whole body vibration ratings for standing

Vibration Total Value (m/s^2)	Comfort Level	Color Code
< 0.23	Not uncomfortable	Green
≥ 0.23 and < 0.5	A little uncomfortable	Yellow
> 0.5 and < 1.2	Fairly uncomfortable	Brown
>1.2 and < 2.3	Uncomfortable	Red
≥ 2.3	Extremely uncomfortable	Red

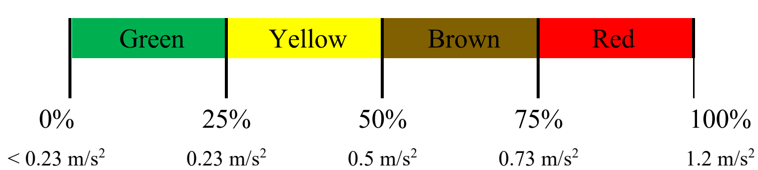

Figure 7. Whole body vibration scoring for standing

Based on the scoring above, the percentage score for the whole body vibration for sitting case can be determined as:

$$WV_t\% = max\left(0, \frac{WV - 0.315}{1.26}\right) \times 100\%, \quad (11)$$

The percentage score for the whole body vibration for the standing case can be determined as:

$$WV_n\% = max\left(0, \frac{WV}{0.92}\right) \times 100\%, \quad (12)$$

where WV is the calculated value of the energy expenditure, WV_t is the percentage score for the sitting case, and WV_n is the percentage score for the standing case.

3.2.4 Illumination

Like other workplace environmental conditions, lighting affects worker's performance and safety. Proper selection of lighting and illumination levels can enhance and guide worker activities. Poor or inadequate lighting can lead to eye fatigue and cause workers to make mistakes, resulting in safety hazards and lower productivity. Light might come directly from sun or from a light fixture. Depending on task and place, the type of required lighting could extend from excessively diffused narrow and focus. In common, light-emitting diodes (LEDs) are an appropriate choice when focus or narrow lighting is needed and fluorescent lighting is considered suitable when wide lighting is required. A balanced and adequate level of lighting in the worksite is an important factor to establish safe, economical and productive working environment. The illumination limits recommended by OSHA are shown in Table 7 and the scoring of illumination risk is shown in Figure 8.

Table 7. Minimum illumination intensities recommended by OSHA

Foot-Candles	Area of Operation or Task	Code
3	General construction areas, concrete placement, excavation and waste areas, access ways, active storage areas, loading platforms, refueling, and field maintenance areas.	A
5	Indoors: warehouses, corridors, hallways, and exit ways.	B
5	Tunnels, shafts, and general underground work areas: (Exception: minimum of 10 foot-candles is required at tunnel and shaft heading during drilling, mucking, and scaling. Bureau of Mines approved cap lights shall be acceptable for use in the tunnel heading)	C
10	General construction plant and shops (e.g., batch plants, screening plants, mechanical and electrical equipment rooms, carpenter shops, rigging lofts and active store rooms, mess halls, and indoor toilets and workrooms.)	D
30	First aid stations, infirmaries, and offices.	E

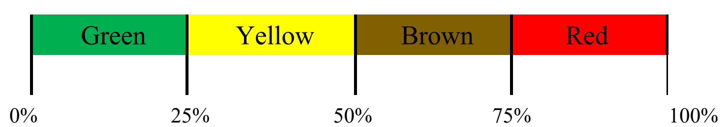

Figure 8. Scoring of illumination

The illumination score can be calculated as:

$$IL\% = \left[\min\left(1, \max\left(0, 1.25 - \frac{IL}{X}\right)\right)\right] \times 100\%, \quad (13)$$

where X = 3 for area code A, X = 5 for area codes B and C, X = 10 for area code D, and X = 30 for area code E. IL is the measured value in Foot-Candles of the illumination in the workplace.

3.2.5 Temperature

Thermal comfort is important for worker health and performance. Several factors affect the heat exchange between human body and environment including: air temperature, air humidity, air movement velocity, radiative heating, excretion levels, clothing, and duration of exposure. To assess thermal conditions of workplace environment, several measures have been developed. Examples of these measures include dry bulb air temperature and radiant temperature. Thermal indexes have been used to predict the thermal comfort and thermal effect. Thermal indexes include Windchill Index, Heat Stress Index (HSI), Effective Temperature (ET), and Wet Bulb Global Temperature (WBGT). HIS and WBGT take into consideration humidity, air movement, exertion levels, and radiant heat. WBGT is the most recent index and is easier to calculate than HIS. WBGT is recommended by both ACGIH and OSHA (Lehto and Buck, 2008, p. 152). The standard values for WBGT are identified by ACGIH as shown in Table 8. WBGT is calculated as:

1. Indoor or outdoor with no solar load:
   $WBGT = 0.7\,NWB + 0.3\,GT$ ……………………………………...………..……………………….………… (14)
2. Outdoor with solar load:
   $WBGT = 0.7\,\text{NWB} + 0.2\,\text{GT} + 0.1\,\text{DB}$ ………………………...………...……………...……...……… (15)

where, NWB is the natural wet-bulb temperature, DB is dry-bulb (air) temperature, and GT is globe thermometer temperature. If there are multiple exposures, the average is calculated as follows:

$$\text{Average WBGT} = \frac{\sum_{i=1}^{n} WBGT_i \times t_i}{\sum_{i=1}^{n} t_i} \quad \text{……………………..……………………………...………… (16)}$$

Table 8. Permissible heat exposure threshold limit value (based on ACGIH)

Work/Rest Regimen	Work Load		
	Light	Moderate	Heavy
Continuous work	30.0ºC (86ºF)	26.7ºC (80ºF)	25.0ºC (77ºF)
75% Work, 25% rest	30.6ºC (87ºF)	28.6ºC (82ºF)	25.9ºC (78ºF)
50% Work, 50% rest	31.4ºC (89ºF)	29.4ºC (85ºF)	27.9ºC (82ºF)
25% Work, 75% rest	32.2ºC (90ºF)	31.1ºC (88ºF)	30.0ºC (86ºF)

The values in Table 9 are based on the assumption that workers are fully clothed with adequate water and salt intake. It is also assumed that WBGT of the resting place is the same or very close to that of the workplace. According to HSE (2013), the Approved Code of Practice suggests that minimum temperature in a workplace should normally be at least 16ºC. If the work involves rigorous physical effort, the temperature should be at least 13ºC. However, these temperatures are not absolute legal requirements; the employer has a duty to determine what reasonable comfort will be in the particular circumstances. Based on this, the minimum values for workplace temperature can be specified as shown in Table 9. The organization can also identify its own limits for the minimum temperature values based on its employee requirements. The scoring for workplace temperature is shown in Figure 9.

Table 9. Minimum heat exposure values

Work/Rest Regimen	Work Load		
	Light	Moderate	Heavy
Continuous work	16.0ºC (60.8ºF)	14.5ºC (58.1ºF)	13.0ºC (55.4ºF)
75% Work, 25% rest	16.6ºC (61.9ºF)	16.4ºC (61.5ºF)	13.9ºC (57.0ºF)
50% Work, 50% rest	17.4ºC (63.3ºF)	17.2ºC (63.0ºF)	15.9ºC (60.6ºF)
25% Work, 75% rest	18.2ºC (64.8ºF)	18.9ºC (66.0ºF)	18.0ºC (64.4ºF)

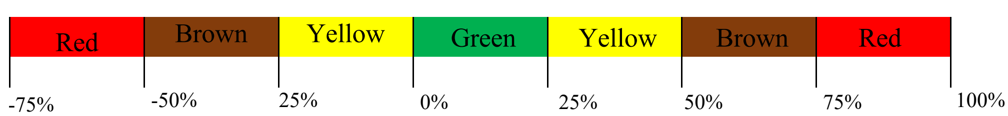

Figure 9. Scoring of temperature

The temperature score for the light work load can be calculate as:

$$TM\% = \left[\frac{WBGT - (21.8 + X)}{11.2}\right] \times 100\%, \quad \text{……………………………..…………………..……. (17)}$$

where X = 0 for continuous work, X= 0.4 for 25% rest, X = 1.2 for 50% rest, and X = 2 for 75% rest. The temperature score for the moderate work load can be calculate as:

$$TM\% = \left[\frac{WBGT - (19.4 + X)}{9.8}\right] \times 100\%, \quad \text{………..……….…………..……...……… (18)}$$

where X = 0 for continuous work, X= 1.9 for 25% rest, X = 2.7 for 50% rest, and X = 4.4 for 75% rest. The temperature score for the heavy work load can be calculate as:

$$TM\% = \left[\frac{WBGT - (17.8 + X)}{9.6} \right] \times 100\%, \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (19)$$

where X = 0 for continuous work, X= 0.9 for 25% rest, X = 2.9 for 50% rest, and X = 5 for 75% rest.

3.2.6 Posture

Ergonomically designed workplace avoids the awkward postures that can negatively influence the workers' productivity and cause fatigue. In order to design posture-friendly workplace, you need to know the concept of neutral body position. In suitable working postures, body weight is distributed evenly to the front, back and the sides of the feet. It is vital to keep the body in the neutral position. This can reduce the stress, pressure on the muscles, and skeletal system and decrease the potential risk of having a musculoskeletal disorder (MSD). The positions of the parts of the body, like arm, head, and wrist, will need to be aligned and not in awkward positions. Along with providing posture-friendly working environment, working in the same working posture, repetitive postures or sitting in the same position for long period of time can lead to fatigues of the body muscles. This in return can reduce the quality of the work and increase unneeded motions, discomfort, and time to accomplish the job (Aqlan *et al.*, 2013). The posture of the workers while they are performing their job is an important factor that impacts the required energy to accomplish that job. Different jobs require different postures to be accomplished. Several ergonomic tools were developed to assess the posture and/or stress risks. These tools include: NIOSH lifting equation, Ovako Working Posture Analyzing System (OWAS), RULA, REBA, Quick Exposure Check (QEC), Strain Index, and Comfort Checklists. In this research, OWAS method is considered which was developed by Karhu *et al*. (1977). OWAS is based on ratings of working postures and it is easy to use. OWAS identifies four work postures for the back, three for the arms, seven for the lower limbs, and three categories for the weight of load handles or amount of force used (see Table 10). Combinations of these four categories are classified by the degree of their impact on the musculoskeletal system for all posture combinations. The degrees of the assessed harmfulness of these posture–load combinations are grouped into four action categories, which indicate the urgency for the required workplace interventions: action category 1: normal postures, which do not need any special attention; action category 2: postures must be considered during the next regular check of working methods; action category 3: postures need consideration in the near future; action category 4: postures need immediate consideration (see Figure 10). The scoring for posture is shown in Figure 11.

Table 10. Ovako postures code definition

Body Part	OWAS Code	Description of Position
Back	1	Back straight
	2	Back bent
	3	Back twisted
	4	Back bent and twisted
Arm	1	Both arms below shoulder level
	2	One arm at or above shoulder level
	3	Both arms at or above shoulder level
Legs	1	Sitting
	2	Standing on both hands
	3	Standing on one straight leg
	4	Standing or squatting on both feet, knees bent
	5	Standing or squatting on one foot, knees bent
	6	Kneeling on one or both knee
	7	Walking or moving
Load handle	1	Load < 10kg
	2	10kg < Load < 20kg
	3	Load > 20kg

Back	Arms	1			2			3			4			5			6			7			Legs
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	Load Handled
1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	1	1	1	1	1	1	
	2	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	1	1	1	1	1	1	
	3	1	1	1	1	1	1	1	1	1	2	2	3	2	2	3	1	1	1	1	1	2	
2	1	2	2	3	2	2	3	2	2	3	3	3	3	3	3	3	2	2	2	2	3	3	
	2	2	2	3	2	2	3	2	3	3	3	4	4	3	4	4	3	3	4	2	3	4	
	3	3	3	4	2	2	3	3	3	3	3	4	4	4	4	4	4	4	4	2	3	4	
3	1	1	1	1	1	1	1	1	1	2	3	3	3	4	4	4	1	1	1	1	1	1	
	2	2	2	3	1	1	1	1	1	2	4	4	4	4	4	4	3	3	3	1	1	1	
	3	2	2	3	1	1	1	2	3	3	4	4	4	4	4	4	4	4	4	1	1	1	
4	1	2	3	3	2	2	3	2	2	3	4	4	4	4	4	4	4	4	4	2	3	4	
	2	3	3	4	2	3	4	3	3	4	4	4	4	4	4	4	4	4	4	2	3	4	
	3	4	4	4	2	3	4	3	3	4	4	4	4	4	4	4	4	4	4	2	3	4	

Figure 10. Action category for OWAS (Chowdhury et al., 2012)

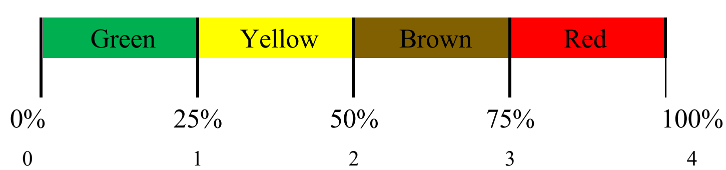

Figure 11. posture scoring

3.4 Calculating and Prioritizing Ergonomic Risks

In order to assess the ergonomic risk and determine its level, risk calculation is required. Once the risk is calculated, it is converted to a score between 0 and 100% based on the proposed ergonomic risk scoring system. The scores are then plotted on a radar chart (see Figure 12) to determine the levels of the risks and their priority. The ergonomic risk radar chart is divided into four areas: green (0-25%), yellow (26-50%), brown (51-75%), and red (76-100%). Mitigating ergonomic risks can be achieved by implementing administrative controls, engineering controls, and personal protective equipment (PPE). To mitigate the risks, the possible controls that can be used are determined. Table 11 shows the mitigation strategies for the ergonomic risks.

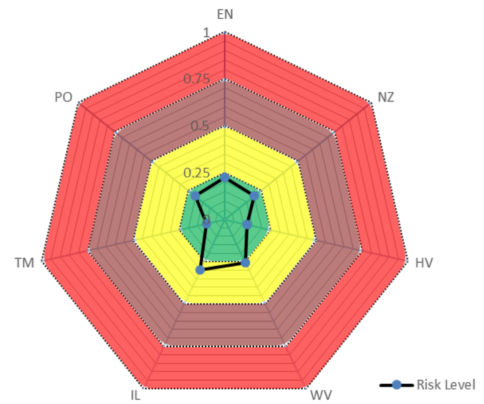

Figure 12. Radar chart for ergonomic risk

Table 11. Mitigation strategies for ergonomic risks

Ergonomic Risk	Administrative Controls	Engineering Controls	Personal Protective Equipment
Energy Expenditure	Operator Training, Rest, Breaks	Job redesign	Light clothing
Noise		Noise Shields	Ear plugs
Hand-Arm Vibration		Tool Change / redesign	Gloves
Whole Body Vibration		Tool Change / redesign	Vibration absorbing material
Illumination		Light Change / Adjustment	Safety glasses
Temperature		Proper Air Conditioning	Protective clothing
Posture/Force		Job redesign	Lifting Aids

4. Case Study: Ergonomic Assessment in a Manufacturing Environment

Ergonomic risk assessment in manufacturing environments is the foundation of the occupational safety and health in the organization. The scoring system for ergonomic assessment was used to assess the occupational ergonomic risks in an electronic manufacturing environment. A specific process was selected which presents potential ergonomic risks to the operators. The company's goal is to have all the risk factors in the green level (low risks). The description of the process is as follows: The process represents a test process for electronic parts. The operator receives the parts in a transportation cart from the downstream process. The weight of each electronic part is 15kg. The operator first enters the part information into the computer which takes about two minutes. The operator bends to take the electronic part from the cart, holds it, kneels and then plugs it into a dedicated slot in the test station. This kneeling position can harm the operator's back and also the energy expenditure for this task is high. All the seven ergonomic risk factors were assessed using the proposed framework and it was found that the two factors that represent high risk to the operators are Posture and Energy Expenditure with scores of 76.0% and 52.5%, respectively. Corrective actions were then implemented to bring these two risk factors to the green level. The corrective actions included: eliminating the kneeling and bending postures of the operator by redesigning transportation carts and providing adjustable seats so that operator does not have to kneel or bend, reducing number of parts per operator in one shift from 120 parts (peak) to 80 parts, and reconstructing work shifts for operators to increase rest period. The test process was evaluated again after actions were implemented and it was found that both risks were reduced to less than 25% (see Figure 13, right).

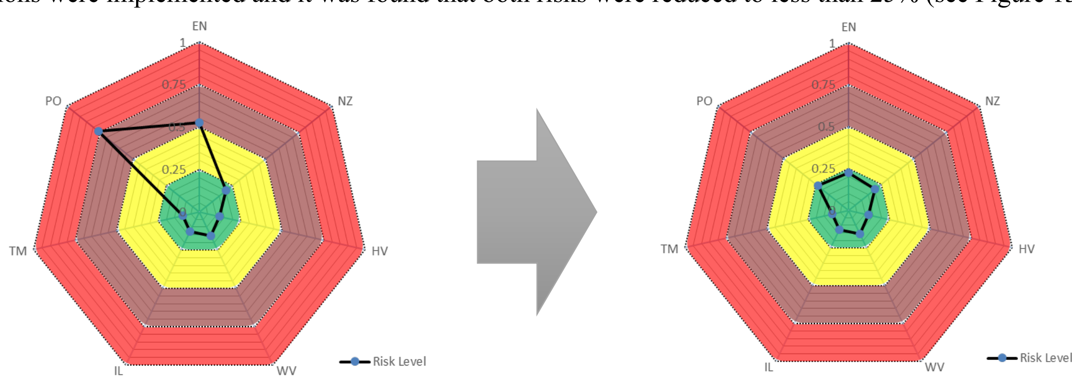

Figure 13. Ergonomic risk calculation and prioritization (before and after mitigation)

5. Conclusions and Future Work

This paper proposed a framework for ergonomic risk assessment by developing a scoring system that converts the measured value of the ergonomic risk into a percentage value between 0 and 100. Furthermore, the risk scores are divided into four levels: red, brown, yellow, and green. The proposed scoring systems makes it easy for the decision makers to determine whether a given ergonomic risk needs to be mitigated or not. A case study from an electronic manufacturing was presented to assess the applicability of the scoring system. The proposed framework can also be applied to other environments where ergonomic risks can exist. One main challenge of the proposed methodology is measuring the current values of the ergonomic risk factors in the workplace. Measurement tools should be available for this purpose. A possible extension to the proposed methodology is developing a software tool that can automatically identify the values of the ergonomic risk factors, convert then values into scores, and then prioritize them and highlight the high risks. This also requires hardware devices (sensors) that can measure the values that will be used by the software.

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