COMPUTER 3D MODEL-BASED PHYSCIAL DEMAND AND ERGONOMIC ASSESSMENT OF BUILDINGS MECHANICAL SYSTEM CONSTRUCTION

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ABSTRACT

Mechanical System including pipes supplied air-condition, heating, and sprinkler are the most time-consuming and complexity to coordinate and manage on a construction site. Moving the construction of mechanical system to a factory (assembly line) will overcome these challenges. The 3D visualization proved to be an effective tool to streamline the processes of constructing the mechanical system on a production line, assisting in investigating the best method of balancing the flow of activities and optimize the resources utilization. There are many advantages to move the construction of mechanical system from on-site to off-site for high productivity, cost and time reduction. Although degrees of automation applied in a factory setting, many activities still demand considerable physical effort. Observation techniques used to measure the physical demand of the activities performed to assemble the mechanical system is time-consuming and requires the involvement of human subject in the study. This paper presents a 3D visualization physical demand assessment (Knee and back) of workers. Based on the information using 3D visualization without visiting the site, physical demand can be assessed in order to measure the effect of changes to the construction method, the tools used and the operation height on the stress applied to knee and back of workers. Findings would give an insight on the potential injury and help to identify the ergonomic issues leading to the discomfort in the lower back and knees of the workers. The ergonomic assessment techniques could assist the early identification of work-related musculoskeletal concerns and help prioritize jobs for intervention in the construction field.

Keywords: 3D visualization, Physical Demand Assessment, Mechanical System, Module, Production Line, Construction.

1. INTRODUCTION

Modular is one of popular construction methods or processes for constructing effectively buildings with lower cost in decades. Production managers and researchers have tried to apply concepts of various disciplines such as lean, simulation, and visualization into the manufacturing industry in order to improve productivity and reduce cost by developing process flow, material handling, and site layout. However, these efforts have not been fully succeed yet. They have realized that their purposes could not be fully achieved without improving construction workers' performances related to all processes of manufacturing production line. Construction workers are at significant risk of work-related musculoskeletal injury (Schneider 2001). Construction laborers perform many physical demanding tasks including cleaning, assembling, preparing the construction site, loading and unloading material for building, operating power tools, operating machines. These activities expose worker to ergonomic risk factors such as awkward postures, heavy lifting, repetitive motions, unsafe environment, and organization. The risk factors lead to increase numerous claims, lose time days and occur five types of accidents, which are falls, overexertion, struck by an object, bodily reaction, exertion and slip, affected various parts of the body: Back, Foot/Ankle, Hands, Trunk, Hand(s)/Wrists, and knees. There is a need to identify the possible risk factors in order to prevent the accidents/illness and improve as the safe and health workplaces for workers. Keyserling et al. (1993) define that the goal of ergonomic analysis is to eliminate or significantly reduce worker exposure to risk hazards. The ergonomic analysis including a detailed ergonomic hazard quantification and rating of the daily work activities and tasks is required in order to identify risk factors and reduce potential works related musculoskeletal disorders (MSDs). This analysis is powerful technique to assess the hazards associated with exertion and overexertion during construction work activities and implementing appropriate and proactive occupational health and safety solutions before onset of a work related musculoskeletal disorder (Inyang and Al-Hussein 2011). Hess et al. (2004) have focused on decreasing the risk of low-back disorder group membership to introduce an ergonomic innovation, assessing exposure, and applying a participatory intervention approach in construction. The partial ergonomic risk analysis of work activities have been implemented by existing ergonomic analysis models: Ovako work posture analysis system (Karhu et al. 1997), Rapid entire body assessment (Hignett and McAtamney 2000), and Rapid upper limb assessment (McAtamney and Corlett 1993). Human being is easily influenced by environmental factors and time for their performance. Inyang and Al-Hussein (2011) suggest the comprehensive body part ergonomic analysis considered factors influenced to workers' performance. It also provides opportunities for more detailed analysis of risk cause and source. Hallowell and Gambatese (2009) have evaluated activities-based safety risk quantification for concrete formwork construction. This paper uses the comprehensive ergonomic analysis to implement ergonomic assessment in order to enhance workers safety and provide great beneficial to ergonomists and construction managers in the mechanical system of a manufacturing production line.

In recent years, 3D visualization is developed by many researchers and planners for construction management, productivity and cost analysis, resource management, and assessment of site layout. It could be used to experiment on a computer screen in order to avoid potential costly on-site error before implementation in the real world for reducing time-consuming and cost. The dynamic graphical depiction of 3D visualization provides detailed information such as the state of each task at a specific time, work-space required for construction activities to be executed safely and productively, and the state of each worker at specific work time in specific work task (Han 2010). Although 3D visualization has proved as an effective tool for various purposes in construction industry, it has not been fully implemented with ergonomic analysis. Feyen et al. (2000) have developed Three-Dimensional Static Strength Prediction Program (3DSSPP)/AutoCAD interface as a proactive biomechanical risk analysis tool based on postural, static and dynamic load analysis functionalities and methods for minimizing risk of injuries at the earliest stages of design. Lamkull et al. (2007) have investigated whether a combination of visualizations and objective ergonomic assessment methods is effective. These researches used only parts of 3D visualization functionalities to assess partial physical demands at specific human postural in specific work activities. To implement comprehensive ergonomic assessment, data collection should be implemented first. There are three types of data collection: 1) self-report; 2) physiological measurement; 3) observation method. Self-reports from workers can be used to collect data based on questionnaires, interview and workers diaries. Physiological measurements using monitoring instruments that rely on sensors attached directly to the subject for the measurement of exposure variables at work (David 2005). The observation method is used in the ergonomic analysis methods for calculating physical demands. However, the observation in ergonomic analysis is the most time-consuming process, increases cost, and no opportunities for implementation in the early design stage of a project. 3D visualization could be one of effective tool for observation without visiting on-site which lead to reduce time and cost. This paper describes that a comprehensive ergonomic assessment is implemented with 3D visualization as an observation tool for data collection without visiting on-site but not include any solutions for avoiding risk hazards identified.

2. ERGONOMIC ANLYSIS WITH 3D VISUALIZATION

The process flow of comprehensive ergonomic assessment with 3D visualization describes in Figure 1. Based on 3D visualization as an observation tool, required information for ergonomic analysis without visiting on-site is collected:

- Tasks, activities, scope, and size of project information for work activity duration.
- Awkward posture, repetition, force and static loading, and contact stress for body part ergonomic analysis.
- Floor layout, work rates, and rest and recovery cycles of work plan for work rate rest and recovery cycle.

The hand-arm vibration and environmental risk factors such as temperatures of objects handled, noise level in usual conditions and temperature of working condition are also involved in body part ergonomic analysis but 3D visualization does not provide these information. Therefore, self-report method (interviews or questionnaires) from managers and workers could be used to collect data. Then, the comprehensive ergonomic assessment developed by Inyang and Al-Hussein (2011) is implemented with data collected from 3D visualization. The outputs are ergonomic hazard assessment report, construction work best practices, potential Work Related Musculoskeletal Disorder (WRMSD) report, and occupational hazard repository.

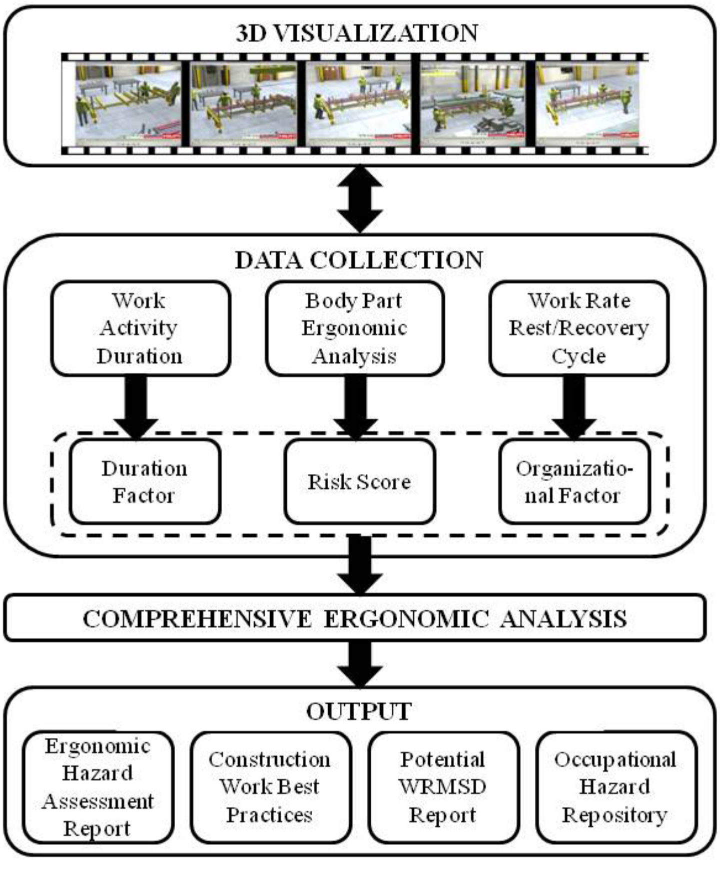

Figure 1: Process Flow of Comprehensive Ergonomic Assessment with 3D Visualization

After data collection, the sequences of the ergonomic assessment are divided by mainly three steps; 1) determine activity duration and effect of existing organizational risk factor using organizational table and 2) identify applicable risk/hazard factors, quantify, rate and classify each risk factor for generating body part risk summary with related tables in Appendix revised in Inyang and Al-Hussein (2011). The detail sequences of ergonomic assessment with equations are described in Figure 2. This method could be helpful to project managers and planners in order to investigate or avoid existed or potential high risks' performances of workers before applying new processes into a factory or designing a new production line for new business. This paper focuses on collecting required information using 3D visualization without time-consuming by visiting on-site and identifying all ergonomic risk hazards, not construction work best practices and occupational hazard repository.

Sept 1. $H_s = P_{hs} + A_s$

Where P_{hs} = Maximum postural hazard score for body part before adjustment

A_s = Risk score adjustment factor

H_s = Total postural hazard score for body part analysed

Sept 1-1. $H_s = \sum R_s$ (Other risk factors for body part)

Sept 2. $$M_o = f(x) = \begin{cases} 0.5, & 0 \le x \le 2 \\ 1, & 2 \le x \le 5 \\ 1.5, & 5 \le x \end{cases}$$

Where x = organizational hazard score

Sept 3. $D_{act} = nCT_{act}$

$D_{exp} = D_{act} \times P_{ex}$

Where n = Number of cycles per day

CT_{act} = Activity cycle time (mins)

P_{ex} = Percent of activity time where a specific body part is exposed to risk factor

D_{exp} = Total Daily duration of risk exposure

D_{act} = Total time spent on activity per day

Sept 4. $$M_d = f(D_{exp}) = \begin{cases} 0, & 0 < D_{exp} \le 10\text{min} \\ 0.5, & 10\text{ min} < D_{exp} \le 30\text{ min} \\ 1.0, & 30\text{ min} < D_{exp} \le 1\text{ hr} \\ 1.5, & 1\text{hr} < D_{exp} \le 2\text{ hrs} \\ 2.0, & 2\text{hrs} < D_{exp} \le 4\text{ hrs} \\ 3.0, & 4\text{hrs} < D_{exp} \end{cases}$$

Sept 5. $R_{hs} = H_s \times M_d \times M_o$

Where R_{hs} = Resultant hazard score

H_s = Hazard score (From Step 1 or Step 1-1)

M_d = Duration exposure multiplier (From Step 4)

M_o = Organizational exposure multiplier (From Step 2)

Sept 6. $$R_r = f(R_{hs}) = \begin{cases} 1, & 0 < R_{hs} < 6 \\ 3, & 6 \le R_{hs} < 13 \\ 6, & 13 \le R_{hs} < 15 \\ 9, & 15 \le R_{hs} \end{cases}$$

Sept 7. $$R_c = f(R_r) = \begin{cases} \text{No risk, } 0 \\ \text{Low risk, } 1 \\ \text{Medium risk, } 3 \\ \text{High risk, } 6 \\ \text{Very high risk, } 9 \end{cases}$$

Figure 2: The Sequences of Ergonomic Assessment

3. A CASE STUDY

3.1 BACKGROUND

The corporation of Kullman is one of the leading modular building manufacturers in the US. It has over 200 employees and has expanded its market to produce a variety of building types, including equipment shelters, schools, dormitories, multi-story residential buildings, correctional facilities, healthcare facilities, and US embassies. The company has considered attending a new construction project, called mercy hospital in Cincinnati, OH, USA, for providing and fastening mechanical system modules. Mechanical System including pipes supplied air-condition, heating, and sprinkler are the most time-consuming and complexity to coordinate and manage on a construction site. Thus, moving the construction of mechanical system to a factory (assembly line) would overcome these challenges. The company wanted to investigate possibility of mechanical system production line and processes to construct mechanical system modules into a building because it has not had experiences related to construct mechanical system modules on a factory and construction site. 3D visualization has been built in order to experiment and simulate mechanical system production line to identify and apply the best method of balancing the flow of activities and optimize the resources utilization before setting up the production line in real world. It has also been used to identify the processes of constructing modules into the hospital. The ergonomic assessment in this case study was investigated for leg and back of body parts of workers in the production line

3.2 Data Collection

Two levels in mechanical system module are defined in a design stage. Total three stations and nine operators in a production line are established that three operators assemble first level MI/MQ box frames (3′- 4″ × 8′ × 20′) and pipes with a crane in Station 1, other three operators install second level MI/MQ frames and pipes with a crane in Station 2, and the others fasten HVAC ducts and wall units in Station 3. Based on the height of MI/MQ box (3' - 4"), three height levels (low, medium, and high) for platform have been divided to find out the best method and balance flow of the production line of mechanical system. Data collection using 3D visualization was implemented and illustrated in Figure 3. Different observed postures were identified at different height levels, respectively. The significant observed postures include flexion of lower back between 20˚ - 60˚ in the low and medium levels, bending of leg (unstable posture) in medium level, and the most stable postures (upright of lower back and straight of leg) identified in high level. The required data for comprehensive ergonomic assessment was not fully collected because 3D visualization could not describe environmental factors (temperatures and noise level), hand arm vibration, and some variables of organizational risk such as mental stress but included force, a part of environmental factor (lighting condition), awkward postures, parts of organizational factors, and contact stress. However, the production line is involved in a factory which environmental risk factors are usually satisfied with proper conditions. The daily duration is an important factor in the comprehensive ergonomic assessment. However, 3D visualization in this case study could not provide exactly and enough process time of an activity because it was built at the early design period of this project. Therefore, the daily duration was assumed 6 hours per day considered 8 hours per day minus break down, rest, and lunch times.

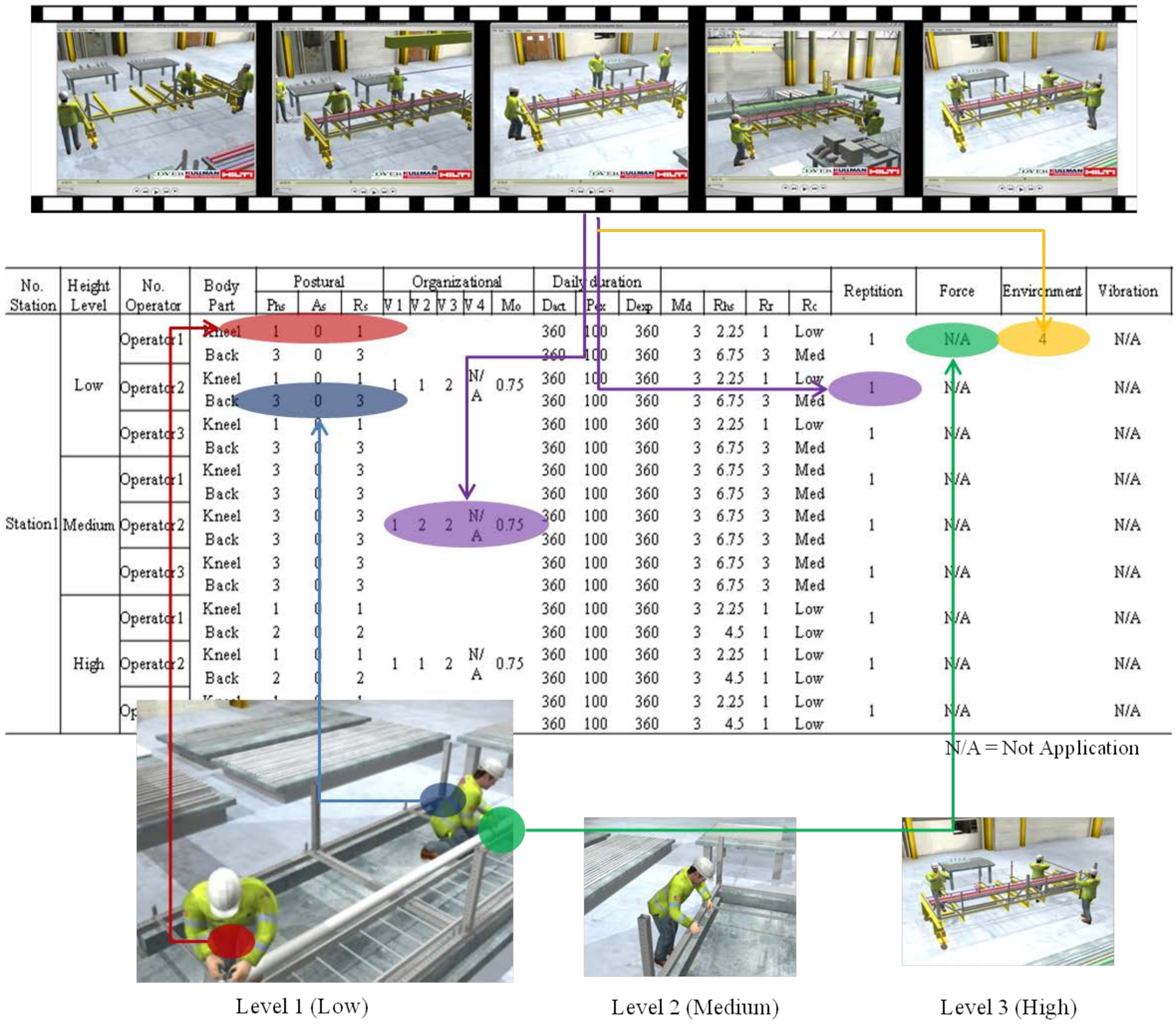

Figure 3: Data Collection with 3D Visualization

3.3 Ergonomic Assessment

This paper focused on the ergonomic assessment related to knee (leg) and lower back of body parts in Station 1 at each height level. Ergonomic risk factors (awkward posture, repetition, environmental and organizational factor, force, and contact stress) were assessed based on the sequences of a comprehensive ergonomic assessment (Figure 2) and data obtained from 3D visualization. Exposure to hand arm vibration, force, and contact stress are not significantly influenced to knee and lower back of body parts and thus not considered in this case. The ergonomic assessment results are summarised in Table 1. The results shows that the highest risk level of heights for knee and back is Level 2 (medium) because the awkward postures identified lead to spend more time to assemble material for mechanical system modules than other levels and influences to increase repetition risk score of an activity. In level 1 (low), both legs for activities usually were straight (walking or sitting) but back was flexion between 20˚ - 60˚ for the activity. Therefore, the back postures expose medium risk but knee postures have low risk. The knee and back of postures were straight and upright in Level 3 (high). The low risk score of postures could lead to decrease repetition risk score related to completed activities earlier than others. The environmental risk is assessed as a low risk factor. A production line is established in a factory which the weather does not influence to workers' performance too much. Thus, environmental risk factors such as lighting conditions, temperatures of objects handled, and temperature of working conditions could be satisfied for providing comfortable condition to workers. According to the results of ergonomic assessment, activities should be implemented on Level 3 (high) for preventing potential high risks of workers.

Height Level	No. Operator	Body Part	With Organization and Duration Factor					
			Posture	Repetition	Force	Environment	Contact stress	Hand Arm Vibration
Level 1 (Low)	Operator 1	Knee	Rr = 1, Low	Rr = 1, Low	N/A	Rr = 1, Low	N/A	N/A
		Back	Rr = 3, Medium	Rr = 3, Medium	N/A	Rr = 1, Low	N/A	N/A
	Operator 2	Knee	Rr = 1, Low	Rr = 1, Low	N/A	Rr = 1, Low	N/A	N/A
		Back	Rr = 3, Medium	Rr = 3, Medium	N/A	Rr = 1, Low	N/A	N/A
	Operator 3	Knee	Rr = 1, Low	Rr = 1, Low	N/A	Rr = 1, Low	N/A	N/A
		Back	Rr = 3, Medium	Rr = 3, Medium	N/A	Rr = 1, Low	N/A	N/A
Level 2 (Medium)	Operator 1	Knee	Rr = 3, Medium	Rr = 3, Medium	N/A	Rr = 1, Low	N/A	N/A
		Back	Rr = 3, Medium	Rr = 3, Medium	N/A	Rr = 1, Low	N/A	N/A
	Operator 2	Knee	Rr = 3, Medium	Rr = 3, Medium	N/A	Rr = 1, Low	N/A	N/A
		Back	Rr = 3, Medium	Rr = 3, Medium	N/A	Rr = 1, Low	N/A	N/A
	Operator 3	Knee	Rr = 3, Medium	Rr = 3, Medium	N/A	Rr = 1, Low	N/A	N/A
		Back	Rr = 3, Medium	Rr = 3, Medium	N/A	Rr = 1, Low	N/A	N/A
Level 3 (High)	Operator 1	Knee	Rr = 1, Low	Rr = 1, Low	N/A	Rr = 1, Low	N/A	N/A
		Back	Rr = 1, Low	Rr = 1, Low	N/A	Rr = 1, Low	N/A	N/A
	Operator 2	Knee	Rr = 1, Low	Rr = 1, Low	N/A	Rr = 1, Low	N/A	N/A
		Back	Rr = 1, Low	Rr = 1, Low	N/A	Rr = 1, Low	N/A	N/A
	Operator 3	Knee	Rr = 1, Low	Rr = 1, Low	N/A	Rr = 1, Low	N/A	N/A
		Back	Rr = 1, Low	Rr = 1, Low	N/A	Rr = 1, Low	N/A	N/A

N/A = Not Application
Rr = Risk Rating

Table 1: Ergonomic Assessment Results

4. CONCLUSION

3D visualization is identified as an effective tool for various purposes such as productivity and cost analysis, resource management, and assessment of site layout in order to experiment and simulate on a computer screen for preventing costly on-site error before implementation in the real world for reducing time-consuming and cost. The dynamic graphical description of 3D visualization provides detailed information including state of each task at specific time, work-space required for activities to be executed safely and productively, material handling method, and the state of each worker at specific process time in particular tasks. 3D visualization was built to streamline the processes of constructing the mechanical system on a production line, assisting in investigating the best method of balancing the flow of activities and optimize the resources utilization in a case study. The observation spent several weeks is usually the most time-consuming process to have exactly and enough data and results for ergonomic analysis. This paper introduces a time-saving observation method for ergonomic assessment that has been successfully implemented with 3D visualization as an observation tool in order to identify and quantify risk hazards in a case study. Especially, this method could be useful at the earliest design stage of a project which observation method could not be implemented because not existed yet. The case study identified that postures, repetition, force/static, contact stress, and parts of environment factors were involved in the 3D visualization. However, hand arm vibration, mental stress in organizational risk, and temperatures were not observed in the 3D visualization. The interviews or questionnaires could be used for these information. Findings would give an insight on the potential injury and help to identify the ergonomic issues leading to the discomfort in the lower back and knees of the workers. The ergonomic assessment techniques with 3D visualization could assist the early identification of work-related musculoskeletal concerns, help prioritize jobs for intervention in the construction field, and leads to reduce time and cost for observation of ergonomic assessment without visiting on-site and at the early design stage of a project.

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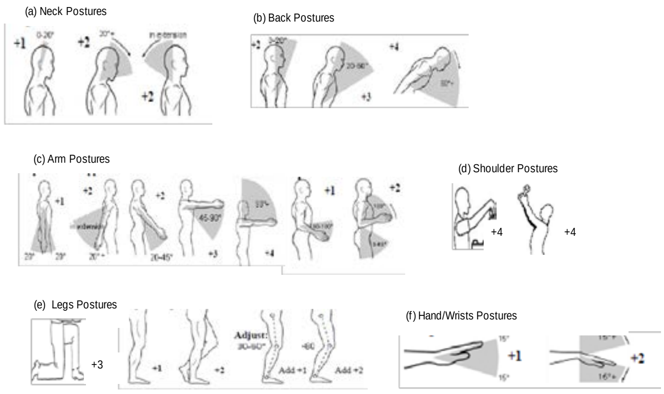
APPENDIX

Postural analysis

Body Part	Posture	Risk Score	Adjust
Upper Back	Upright	1	Add(+1) If twisting of flexing to side
	0° - 20° Flexion	2	
	0° - 20° Extension		
	20° - 60° Flexion	3	
	>20° Extension		
	>60° Flexion	4	
Upper Arm	20° Extension - 20° Flexion	1	Add(+1) If arm is abducted or rotated. Add(+1) if leaning, arm supported, posture is gravity assisted
	>20° Extension	2	
	20° - 45° Flexion		
	45° - 90° Flexion	3	
	> 90° Flexion	4	
Lower Arm	60° - 100° Flexion	1	
	< 60° Flexion	2	
	> 100° Flexion		
Shoulder	Raised	4	N/A
Hand and Wrist	0° - 15° Flexion/ Extension	3	Add(+2) if wrist is deviated or twisted
	> 15° Flexion/ Extension	6	
Neck	0°- 20° Flexion	1	Add(+1) if twisting of flexing to side
	> 20° Flexion/ Extension	2	
Leg	Both legs straight (walking or sitting)	1	Add(+1) if knee bent 30°-60°
	One leg bent slightly (unstable posture)	2	
	Squatting or kneeling	3	



Repetition Risk

Frequency	Frequency (min)	Hazard Score
> 5min/cycle	1×/>5min	0
> 1min/cycle	1×/ 2-5min	1
(30-60)sec/cycle	(1×-2×)/min	3
(15-30)sec/cycle	(2×-4×)/min	6
< 15 sec/cycle	(>=4×)/min	9

Contact stress risk

Exposure Variables	Condition	Risk
Contact stress from object	Little/no pressure exerted on skin	1
	Some pressure exerted on skin	2
	High pressure on skin resulting in marks or depressions on skin	3
using hand or body part with force to strike an object or tool or body part is subjected to impact force	Hand or body part impacts soft material or rounded object	1
	Hand or body part occasionally impacts hard objec/is impacted	2
	Hand or body part frequently impacts hard object/ is impacted	3

Force/static load risk

Exposure Variables	Condition	Risk Score
Weight of object pulled lifted, pushed or rotated	< 8kg (17lbs) for 2 hands, or < 4kg	0.3
	8kg-23kg (17-51 lbs) for 2 hands, or 4-11.5kg (8.5-25lbs) for one hand	0.6
	>23kg (51 lbs) for 2 hands, or >11.5kg (25lbs) for one hand	1
Location of load(>17lbs) at start or end of lift	Between hip and shoulder	0.3
	Between knee and hip height	0.6
	Below knee or above shoulder height	1
Carrying a load(>17lbs)	<3m (10ft)	0.3
	3-9m (10-30ft)	0.6
	>9m (30ft)	1
Load Characteristics (any weight)	Load easy to carry(wrt size, shape, weight distribution), has proper handles	0.3
	Load easy to manageable(wrt size, shape, weight distribution), has proper handles	0.6
	Load awkward to carry (wrt size, shape, weight distribution), has proper handles	1
Pushing, pulling or rotating a load	<2m (6.5ft)	0.3
	2-60 m (6.5 - 200 ft)	0.6
	> 60 m (200 ft)	1
Seated or squatted lifting or lowering	<1kg (2lbs)	0.3
	1 - 5 kg (2 - 11lbs)	0.6
	>5 kg (11lbs)	1

Environmental factor risk analysis and rating

Exposure Variables	Condition	Risk Score
Lighting Condition	Appropriate lighting worker's task allows comfortable posture	0.5
	Light changes results in worker adopting awkward posture	1
	Low/high light level. May lead to hunched worker posture	1.5
Temperatures of objects handled	Comfortably warm objects are handled. Hands not exposed to uncomfortably cold temperatures	0.5
	Moderately warm object or moderately cold temperatures	1
	Object very cold or exhaust on hands	1.5
Noise level in usual conditions	Noise level comfortable and unnoticeable	0.5
	Occassionally uncomfortable and distracting	1
	Very loud, may cause hearing loss	1.5
Temperature of working conditions (plus effect of seasonal changes)	Comfortable working temperature	0.5
	Working temperature occassionally uncomfortable	1
	Working temperature frequently ncomfortable and appropriate PPE not available	1.5

Organizational risk

Exposure Variables	Condition	Risk Score
Daily work recover cycles	Daily work consistent with regular pauses	0.5
	Daily work has infrequent pauses	1
	Daily work has no regular pauses	1.5
Work rate	No diffculty keeping pace	0.5
	Slow or steady motions	1
	Rapid steady motion/difficulty keeping pace	1.5
Worker's control over the work	Complete control over work/flexibility with deadlines	0.5
	Work paced, but worker has some flexibility over deadlines	1
	Work is machine paced, worker does not control pace at will. Little flexibility with deadlines	1.5
Mental stress	Worker does not find task to be mentally stressful	0.5
	Task is sometimes mentally stressful	1
	Worker always feels mental stress	1.5

Hand arm vibration

Daily exposure range (m/s2)	Total daily exposure points	Hazard Score
0-2.2	<= 81	1
2.2-4.5	81 - 338	3
4.5-8.0	338 - 1025	6
>8.0	>1025	9