A GENERAL COMPUTER - BASED METHODOLOGY FOR WORK INJURY ANALYSIS IN A PRODUCTION ASSEMBLY LINE

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EMODI CHUKWUMOBI T.

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ABSTRACT

Repetitive injuries have been a major obstacle in production assembly lines all over the world. These injuries have greatly reduced the production efficiency of assembly plants and also negatively affected human health. Various attempts have been made by the Canadian government through the Worker's Compensation Board (WCB) to prevent the occurrences of these injuries because of the associated cost and effects. These attempts failed as the cost of injuries acquired in the workplace continues to increase. For example, in New Zealand alone, the total cost of accidents in 2005, is estimated at $300 million (Accident Compensation Corporation, 2005). In Canada, the number of accepted claims alone amount to 15623 people (Workers Compensation Board of Canada, 2003).

A human body can be viewed as a mechanism that is composed of links and joints controlled by a central nervous system and are subject to stress, strain, fatigue and failure as can be observed on a regular industrial robot. But unlike the robot which is designed proactively, these stress and strain factors could be because of certain conditions such as inappropriate work posture, poor assembly line design, excessive workload, and poor work conditions.

Often, it is almost uncertain to make a conceptual assessment of the appropriate ergonomic design of a production system before the assembly line is built and put in use. This research will propose a general computer-based methodology for analysis of work injuries given an assembly line where human workers perform repetitive operations. The general methodology integrates sophisticated computer software systems for biomechanics simulation with various manual measurement techniques and methods. The research further proposed a simple and handy synthesis method with which problematic areas of assembly line design, with special reference to human work design can be identified and improved. The proposed methodology for analysis and synthesis is then implemented in a real assembly line to understand the effects of different work activities on the human body. Various software packages

and motion tracking techniques will be considered prior to the actual implementation of the final methodology. A rule of thumb table will also be presented as a guideline for the re-design process. The research also proposed a general procedure and specific formula within a specific regional context to calculate the costs of worker injuries in real-life assembly system. This formula thus allows us to obtain the total cost of injuries in a production assembly line, making it possible to optimize the design and operation of the assembly line.

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DEDICATION

TO MY DEAREST PARENTS:

BARRISTER & DR. (MRS.) ORAMALU DOLLY EMODI

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ACRONYMS

AM: ASYMMETRIC MULTIPLIER

CNH: CASE NEW HOLLAND

CLI: COMPOSITE LIFTING INDEX

CM: COUPLING MULTIPLIER

DELMIA V5©: DELMIA VERSION 5.0

DM: DISTANCE MULTIPLIER

FM: FREQUENCY MULTIPLIER

FILI: FREQUENCY-INDEPENDENT LIFTING INDEX

HM: HORIZONTAL MULTIPLIER

IGES: INITIAL GRAPHICS EXCHANGE SPECIFICATION

IMTI: INTEGRATED MANUFACTURING TECHNOLOGIES INSTITUTE

LI: LIFTING INDEX

LC: LOAD CONSTANT

PRO-E: PRO ENGINEER

REBA: RAPID ENTIRE BODY ASSESSMENT

RWL: RECOMMENDED WEIGHT LIMIT

NIOSH: NATIONAL INSTITUTE FOR OCCUPATIONAL SAFETY AND HEALTH

NRC: NATIONAL RESEARCH COUNCIL

RULA: RAPID UPPER LIMB ASSESSMENT

RWL: RECOMMENDED WEIGHT LIMIT

STLI: SINGLE-TASK LIFTING INDEX

SPSS: STATISTICAL PACKAGE FOR THE SOCIAL SCIENCES

STRWL: SINGLE-TASK RECOMMENDED WEIGHT LIMIT

SWCB: SASKATCHEWAN WORKERS COMPENSATION BOARD

UTS: UNIT TASK SIMULATOR

VM: VERTICAL MULTIPLIER

WCB: WORKER'S COMPENSATION BOARD

CHAPTER 1: INTRODUCTION

1.1 MOTIVATION

Various attempts have been made by the Canadian government through the Worker's Compensation Board (WCB) to prevent the occurrences of work related injuries because of the associated cost and effects. The cost of injuries acquired in the workplace in this country has been increasing in the past decade. Labor Canada, in 1994, estimated the total costs of industrial accidents at about $14-billion and these have been increasing periodically. In 1995, WCB costs were estimated at about $5-billion nationally. This cost includes certain factors such as medical expenses, pensions and funeral costs (Labor Canada, 1994). Roughly 6,371 job-related injury deaths, 13.3 million nonfatal injuries, 60,300 disease deaths, and 1,184,000 illnesses occurred in the United States workplace in 1992 alone (Leigh et al, 2000). Ten percent of Canadian adults had a repetitive strain injury (RSI) critical enough to limit their normal activities in 2000/2001 (The Daily and Statistics Canada, 2003).

Injuries caused by musculoskeletal disorder disable 5 million workers each year in the U.S., and these cost about $100 billion annually (Elevia Science Publishers, 1992). Total cost of Injuries in New Zealand alone in 2005 is $300 million (ACC Injury Statistics, 2005). From previous statistics obtained from the Saskatchewan Workers Compensation Board (SWCB), it was extracted that the majority of these non-preventable injuries occur as a result of excessive repetitive motion, over-exertion or poor assembly line design (SWCB, 2004).

Repetitive injuries posed as a result of repetitive operations have been found to affect production efficiency in a great number of ways by increasing production cost and also reducing the quality of the products. This has been a major issue industries and research institutions. The method of approach adopted by these studies seem to pose more injuries to the workers as a worker needs to perform a task to the extreme level of pain to determine if repetitive injuries will occur or not. Some of these experiments are run using the basic principles of psychophysics. The problems associated with this approach call for a better approach where the safe levels of various activities in the plant can be determined and optimized without affecting the current production activity or even causing further injuries.

1.2 PROBLEM STATEMENT

Assembly line and production plant design engineers have found it difficult to incorporate ergonomics information regarding the human operator into their designs (Evans and Chaffin, 1986). A possible approach to this problem is the use of computer aids for the evaluation of human operations in a work place. However, the computer aided approach needs to answer the following questions:

1. What information is required as input to any computer aided system?
2. How can the information be integrated in the proposed software environment and in what format do we require this information?
3. What are those underlying assumptions made during the modeling stage?
4. What are the various recommendations that can lead to an injury free design given an existing assembly line?
5. How can the re-design be incorporated in the current assembly line design while considering constraints in the system?
6. What are the effects of cost on the various changes related to reduction of work injuries?

Some of these questions are not easily understood as the human body is believed to be the most complex system ever existed. There is a need to combine statistical, analytical, and subjective methods in order to obtain valid results. Many studies and computer programs have been developed to address these issues in the context of production line design. None of these have addressed effectively the application of analysis in an actual assembly line, the re-design criteria, and the actual cost of these designs. Hence, the main goal of the study presented in this thesis was to develop an integrated and coherent methodology for analysis, synthesis, and actual cost of work injuries given a typical assembly line such as that illustrated in Chapter 3 of this thesis.

1.3 Objective

The following have been defined as the objectives of this study:

1. To develop a general methodology for analysis of work injuries given an assembly line. The general methodology includes a specification of information that needs to be collected, the processing of information to lead to the results that are related to work injury levels, and the corresponding costs.
2. To study preliminary methodologies for synthesis, especially re-design of an assembly for the purpose of work injury reduction.
3. To apply the methodologies developed in Objective 1 and Objective 2 to a real assembly line in order to demonstrate how the methodologies are used. This will also provide a complete evaluation of the injury situation for this assembly line with an aim to improve the design while reducing work injury and cost.

The various objectives of this study aims at understanding the current state of the art of the assembly line design with consideration to human safety.

1.4 Organization Of Thesis

Chapter 2 will present a background and comprehensive literature review of the existing studies based on the objectives defined in Section 1.3. Chapter 3 presents an example assembly line that will be used as a case study for the implementation of the developed methodologies. Chapter 4 presents the general methodology for analysis and an empirical-based methodology for synthesis or re-design for the purpose of repetitive injury reduction. Chapter 5 presents a detailed process of the analysis and synthesis of the example system presented in Chapter 3 as well as a complete result and evaluation of the injury level situation of the example system. This thesis will be concluded with Chapter 6 which not only provides a conclusion of the current work, but also makes available various recommendations for future work.

CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

2.1 INTRODUCTION

Various studies carried out in human biomechanics and human modeling and simulation for injury analyses are presented in this chapter of the thesis. We also addressed issues related to production lines in a more detailed manner in order to predict how the re-design of this line could affect performance. Hence, the relevant literature will be discussed to understand how previous research has been able to prove or show the correlation between human repetitive movements, injuries, and assembly line designs using different experimental and analytical based approaches. These studies are based on significant effort to ensure a safe work environment that is capable of both improving the efficiency of manufactured products and also reducing human/ material waste encountered during production operations.

2.2 WORK INJURY CLASSIFICATION FROM SWCB POINT OF VIEW

An injury is defined by the Encarta dictionary as anything that can cause physical damage to the body or body part. But Merriam Webster defines injury as anything that hurts, damages, or leads to sustained loss. A work injury is the result of any work related event that causes a need for medical treatment and/or time away from work (SWCB, 2004). The WCB considers each work injury on an individual basis, but in most cases compensation would apply to injuries that occur while a worker is at work, on company premises or on company business as injuries include occupational diseases caused by work. A process of classifying these production assembly line injuries into basic groups is known as injury classification.

The basic injury classification adopted by the WCB is based on bodily locations. The body is divided into various groups and sub groups and injuries are classified based on the part of the body on which these injuries occur.

2.2.1 PART OF BODY CLASSIFICATION

The part of body classes includes the abdomen, ankles, arms, back including the spine and spinal cord, balls, body systems, brains, buttocks, chest, cranial region, digestive system, elbow, eyes, face, foot, forehead, kidney, knees, leg, hips, nose, outer ear, pelvic region, neck, cheek, etc. There are one hundred and thirty seven (137) classifications under this injury scheme.

2.2.2 PART OF BODY GROUP CLASSIFICATION

This is the most widely accepted method of classification adopted by the SWCB. These are classified based on the parts of body group. Various body parts are classified into part of body groups. The part of body group classification includes: (1) body systems, (2) head, (3) lower extremities, (4) multiple body parts, (5) neck-including throat, (6) other body parts, (7) trunk, and (8) upper extremities. Other classifications relevant to this work are diagnosis and diagnosis sub-group. These are discussed in the sections 2.2.3 and 2.2.4.

2.2.3 DIAGNOSIS CLASSIFICATION

The WCB classified various injury types based on the diagnosis. This injury classification includes such elements as sprains, strains, tears, cuts, abrasions, acaraisis, punctures, carpal tunnel syndrome, acute respiratory infections, allergic dermatitis, avulsion, back pain, disc disorder, chest pain, heart burn, etc. There is a total of two hundred and twenty (220) classifications under this group.

2.2.4 DIAGNOSIS SUB-GROUP

This group includes such classifications as traumatic effects of environmental conditions, abnormal findings, bacterial diseases, circulatory system diseases, infectious and parasitic diseases, intracranial injuries, musculoskeletal system and connective tissue diseases and injuries, nervous system and sense organs diseases, respiratory system diseases, etc. There is a total of thirty three (33) different classifications under this group. Various injury diagnoses were grouped into different sub-groups to form the diagnosis sub-groups.

2.3 HUMAN BODY BIOMECHANICS

According to Knapp (2006), the discipline of biomechanics integrates both the laws of physics and the working concepts of engineering to describe the motion of various body segments and the forces acting on these segments. Injury biomechanics incorporates both the knowledge of force and motion with a thorough understanding of functional human anatomy, human biomechanics and human tissue mechanics to discover the possible correlation between external factors and human tissue injuries. Human biomechanics research has also addressed a wide range of topics related to the mechanics of human motion. This research includes examining the mechanical function of muscles, connective tissue, cartilage, skin, nerves, bones, joints, and internal organs. This also includes research that is focused on human movement and performance in a production/assembly line while examining the internal and external forces, loads, moments/torques that produce movement. The biomechanist accepts the valid recommendations of medical diagnosis and is focused on the process that produced the injury which is believed to be the result of internal or external forces on the human body structures (Knapp, 2006).

The human body is like a machine that is subjected to stress and also reacts to this stress. Stress could have a positive effect, keeping the human body alert and ready to avoid danger. Stress can be viewed as negative when a person faces an exertive work load without a break between these activities. These challenges can be acquired through repetitive work. As a result, a person could become overworked, hence leading to stress-related effects such as injury, and tension. Negative stress can disturb the body's internal balance or equilibrium. This could lead to physical symptoms such as headaches, back pain, upset stomach, elevated blood pressure, chest pain, and sleeping problems. Previous research also suggests that stress can either bring or worsen certain symptoms or diseases (Grayson, 2005). Some other factors limit the performance of a human operator. These factors may include muscle strength, spinal force tolerances, body balance, and foot potential. Factor's that limit human ability are dependent on the direction and magnitude of the expected maximal force, posture, age, and the human anthropometry. Following findings based on some experimental results, some of these forces may also be assumed insignificant. Addressing how human physical limits affect decision about work place design has been a major challenge especially when it has been discovered that manual exertions account for serious injuries mostly to musculoskeletal system (Chaffin, 1991). These injuries are believed to comprise of approximately 50% of all work related injuries in the US, cause the disability of about 5 million workers each year, and cost about $100 billion yearly (Chaffin, 1992).

2.4 Some Challenges Associated With Injury Analyses

It has proved extremely difficult to identify the level of injury that could lead to persistent pain. Painful injuries result due to mechanical loading of nerve roots, which can occur for the spinal injuries in both the lower back and neck (Winkelstein, 2003). Mechanical allodynia (MA) is an increased behavioural sensitivity to a non-noxious stimulus and has been observed in the dermatone of injured tissues. Since allodynia is a clinical measure of sensitivity, it provides a useful gauge of nociceptive responses. From previous animal study, compression of neural structures initiates a variety of physiologic responses, including decreased electrical activity, increased edema formation, and increased endoneural pressure around the area of compression (Lundborg, 1984). Irrespective of the evidence obtained on edema formation and increased endoneural pressure locally in nerve roots, no study has simultaneously documented local changes in the nerve root geometry following the compressive injury and how these changes may be linked to the onset and/or maintenance of pain associated behaviors. Hence, a new problem has been discovered by this approach. Further study by Winkelstein (2003) indicates a complicated physiology for injury which likely contributes to the manifestation of pain. Further studies are being considered in tissue rebound/recovery responses for various mechanical magnitudes for better understanding of potential injury mechanisms resulting in pain (Winkelstein, 2003).

One of the major requirements in preventing work injury is being able to predict exactly what exertion requirements are involved in the operations. Currently, regular work measurement systems do not provide this information. In as much as the average time to perform a specific task can be predicted, the physiological and biomechanical demands of work are yet to be identified (Chaffin and Anderson, 1991). Chaffin (1992) also analyzed the concept of human exertion simulation method, as there is a likelihood for individuals without prior knowledge of the complexity behind human-hardware interaction in the industry to depend on computer generated images as real representations of biomechanical stresses on an individual. Hence, there is need for appropriate and accurate representation of human postural requirements (kinematics) of a job, while efficiently understanding the biomechanical consequences of certain types of exertion relative to certain standards. The accurate prediction of human postural requirements in different work settings and for a variety of human population is one of the biggest challenges involved in the use of simulation/CAD tools.

Analysis and evaluation of human body in motion is believed to be a more complex problem as motions can cause peak inertia loads on the body as well as alterations in assumed body postures which will, on an average, cause an initial static analyses to an error by ±30% or more. This has been observed as the main difficulty associated with dynamic analyses (Chaffin, 1991). First, there is no current method of accurately predicting the average postural and inertial loading for different work requirements. On a second note, dynamic strength and tissue tolerance data for working population does not exist. However, it is possible to acquire a body segment motion data using automated video image analyses, by acquiring body segment motion data through direct measurement of a person performing a job. These data can then be evaluated using biomechanical models with the resulting model and joint force predictions being used to guide the improvement of a job, through comparative evaluations. The initial interest in multiple task analyses has been to either predict the time required or the metabolic energy required by an average person performing the job (Keyserling, 1986). Sequential task and postural data are being combined for empirical prediction of the risk of various musculoskeletal injuries believed to be associated with the repetition of forceful exertion under certain postures in different work settings (Keyserling, 1986).

2.5 ANALYTICAL APPROACH USED IN REPETITIVE INJURY ANALYSES

Various research studies addressing basic issues facing production planning in industries have been conducted using the analytical approach. One of these challenges was to maximize labor utilization through the choice of the line building the product, the number of workers assigned to the line, and the line speed (Inman and Jordan 1997).The problem was then formulated using a mixed-integer non-linear programming approach.

A heuristic solution and a branch and bound approach were used in these analyses. The heuristic approach involves the ordering of products and lines in a product or line ranking scheme and writing a basic program guiding the principle activities in the line. The main aim of this approach is to limit labor cost by optimizing line speeds and product assignment (Inman and Jordan, 1997). This approach could face a lot of criticism in the actual implementation because of the various factors in the assembly line which have not been put into consideration or assumed during the mathematical formulation stage. However, this can also act as a basic structure which can be used during the initial optimization stage of any assembly process.

A kinematics model intended to mimic a human operator has been developed (Palm, 2003). This was after the initial confirmation that the simulation of positions and the motions of human operators interacting with machines and other human operations in an assembly environment are essential for ergonomic work place design. These models included both the forward kinematics models and the inverse kinematics models. This method used in generating a human like smooth motion used a point to point trajectory. However, the main target was to create an inverse kinematics model to translate different assembly handling tasks into human like motions (Palm, 2003).

But due to the high level of difficulty associated with the non-linearity of the forward and inverse kinematics models between their joint angles and end effector positions, a decision was made to compute the inverse kinematics using previous experimental results involving the use of markers on the operator's body and cameras to track the motion of the sensors associated with these markers (Palm, 2003). This method could also be extended to such areas as reachability during the optimization or initial design of assembly lines using basic principles of geometry. Some or most of the modeling software packages were developed using basic mathematical/analytical principles. In some case, these principles could be applied directly to address pressing issues in an assembly line **(**Palm, 2003).

Human operators have been placed with respect to specific targets using the principles of geometry. The essence is to optimize such human performance criteria which are formulated as mathematical cost functions that can either be minimized or maximized. This is aimed at placing the operator in such a position as to limit the stress and strain acting on various parts of the operator's body while improving reachability (Abdel Malek et al., 2004). The method used in this work involves: (1) Determining the workers reach envelope, (2) Moving the workers reach envelope towards optimizing the cost function while putting into consideration all the necessary constraints. This method could be very helpful if the human anthropometry is put into consideration during each design process. However, this may not be possible as most human anthropometric data does not include the length of the limbs, and this does not in many occasions have a proportionality with body weight and height as has been confirmed through previous experimental/analytical procedures. Hence using an analytical approach in calculations involving reach will be a difficult task due to the variance in the lengths of human limbs.

2.5.1 ANALYTICAL APPROACH USED BY NIOSH

Several years ago, the National Institute for Occupational Safety and Health (NIOSH) recognized the need to prevent work-related back injuries and published the work practices guide for manual lifting (NIOSH, 1981). This guide contained lifting-related literature, analytical procedures and a lifting equation for calculating a recommended weight for specified two-handed or symmetrical lifting tasks, and a method that could be used in controlling the hazards of low back injury acquired from manual lifting tasks.

Revised 1991 NIOSH lifting equation reflects new findings and provides methods for evaluating asymmetrical lifting tasks, and lifts of objects with less than optimal couplings between the object and the worker's hands. The revised lifting equation provides guidelines for a wider range of lifting tasks than the NIOSH 1981 (Waters, 1998). The main target of this equation is to calculate the Recommended Weight Limit (RWL) and the Lifting Index (LI). The RWL is the recommended weight that nearly all healthy workers could lift over a period of time (up to eight hours) without an increased risk of developing lifting related low back injury or pain with all other parameters kept constant. The LI provides as estimate of the physical stress associated with a manual lifting job. As the LI increases in magnitude, the level of the risk exposure for a given worker also increases, hence putting a good percentage of the workforce in a position of high injury potential. NIOSH predicts that lifting tasks with a LI > 1.0 pose an increased risk for lifting-related low back pain and injury for some fraction of the workforce.

The RWL is defined by the following equation:

$$RWL = LC \times HM \times VM \times DM \times AM \times FM \times CM \qquad (2.1)$$

Table 2.1 presents the various multipliers and their values. Each multiplier is computed using the appropriate equations, tables, and/or task variables. However, in some cases, linear interpolation is used to determine the value of a multiplier and this occurs in situations where these values cannot be directly extracted from a table. The various task variables are presented in Table 2.1a below:

TABLE 2.1: VARIOUS MULTIPLIERS AND THEIR VALUES

		Metric	U.S.
Load Constant	**LC**	23kg	51lb
Horizontal Multiplier	**HM**	(25/H)	(10/H)
Vertical Multiplier	**VM**	1-(.003[V-75])	1-(.0075 [V-30])
Distance Multiplier	**DM**	.82 + (4.5/D)	.82 + (1.8/D)
Asymmetric Multiplier	**AM**	1-(.0032A)	1-(.0032A)
Frequency Multiplier	**FM**	From NIOSH tables	From NIOSH tables
Coupling Multiplier	**CM**	From NIOSH tables	From NIOSH tables

Various standards are also present in reference literature for obtaining the constants FM, CM, H, V, D, A, F, and C presented in tables 2.1 and 2.1a (Waters et al., 1994).

TABLE 2.1B: TASK VARIABLES IN NIOSH EQUATION (Waters et al., 1994)

TASK VARIABLE	**MEANING**
H	HORIZONTAL COMPONENT
V	VERTICAL LOCATION
D	DISTANCE COMPONENT
A	ASYMMETRIC COMPONENT
F	LIFTING FREQUENCY
C	COUPLING COMPONENT

Table 2.1 presents the various formulas for obtaining the NIOSH multipliers. Fig. 2.1 shows the physical location of the horizontal and vertical components with respect to the vertical axis.

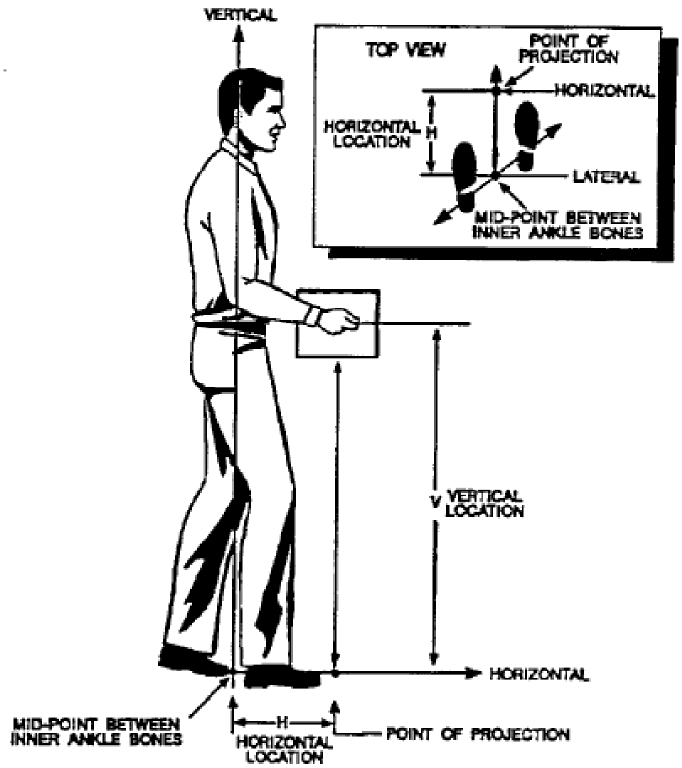

FIGURE 2.1: GRAPHIC REPRESENTATION OF HAND LOCATION (WATERS ET AL., 1994)

The LI provides as estimate of the physical stress associated with a manual lifting job. As the LI increases in magnitude, the level of the risk exposure for a given worker also increases (Waters et al., 1994).

The LI is defined by the following equation and is presented in Waters et al. (1994)

$$LI = \frac{Load\ Weight}{\text{Re}commended\ \ Weight\ Limit} = \frac{L}{RWL} \qquad (2.2)$$

2.5.2 MODIFICATIONS ON REVISED NIOSH EQUATION

A modified model on the NIOSH revised lifting equation known as the compressive lifting model has been developed. The basic claim of this model is the elimination of some limitations on the NIOSH lifting equation. The Comprehensive lifting model is basically using the concept of NIOSH equations but with a few modifications to incorporate such factors as gender and age. Some of the factors considered by the Comprehensive Lifting Model are: (1) Development of age and body weight multiplier (2) The extension of the weight lifting equation above the limit of 75% of female population and 99% of male population, (3) Provision for different task duration other than just a range of values and also adjusting it to represent physiological data rather than psychophysical data, (4) Increasing the upper limit for lifting frequency to a point greater than 4 times/min, (5) Inclusion of stress and temperature variables as NIOSH was designed for ambient temperature values, (6) Basing the asymmetric multiplier on dynamic lifting tasks and avoiding the use of data gathered from static lifting tasks, (7) Base weight and distances which used to be based on psychophysical data from Snook and Ciriello are now based on physiological and biomechanical data (Hildalgo et al., 1997).

Presented below is an equation representing the Comprehensive Lifting Model as proposed by Hildalgo et al. (1997).

$$LC = WB \times H \times V \times D \times F \times TD \times T \times C \times HS \times AG \times BW \qquad (2.3)$$

Where LC= lifting capacity; WB= base weight; H= horizontal distance; V= starting height; D= vertical distance of lift; F =frequency /min; TD= task duration; T =twisting angle factor (degrees); C =coupling factor; HS= heat stress factor; AG =age factor; and BW= body weight factor.

This model is designed to calculate the lifting capacity as was designed initially by NIOSH 1991. Tables were developed by these researchers to provide values for the additional multipliers included in the Comprehensive Lifting Model. The age and body weight multipliers were included in the model based on previous research conducted on cadavers which was used to demonstrate the changes in the compressive strength of the lumber spine based on; (1) increase in body weight, (2) gender, (3) age (Genaidy et al., 1993).

The obtained data from experiments were fitted into a regression equation to obtain the following relationship used in calculating the compressive strength as a function of gender, age, and increase in body weight. In literary terms, the compressive strength refers to the capacity of the human body to withstand pushing forces directed in the axial direction.

$$CS = -13331.2 - \{73.7 \times AGE\} - \{962.6 \times GENDER\} + \{403 \times LMS\} + \{79.8 \times BW\} \quad (2.4)$$

Where GENDER= 1 for male subjects and 2 for female subjects; CS = compressive strength (N); AGE = age (years); LMS = lumbar motion segment $[L4/L5 = 47]$; and BW = body weight (kg) (Genaidy et al., 1993).

The importance of this research cannot be overestimated. However, the claims made by Genaidy et al. (1993), need to be investigated further. If these information are validated, there is need to switch to these more compressive equations in place of the NIOSH equations. Several other models have been developed for manual operations such as lowering, pushing, pulling, and carrying activities. As was the case in the NIOSH 1991 equation, these lifting models were also formed from psychophysical data established by Snook and Ciriello (Shoaf et al., 1997). The authors summarized the various models to accept some of their changes and claims. These claims and observations make sense. There is therefore need to verify and possibly accept the changes for more valid ergonomics results.

2.5.3 ANALYTICAL APPROACH IN WORK LOAD BALANCING

The energy expenditure is a mathematical model that was developed using a physiological approach and which allows the analyst to estimate the metabolic rate (energy expenditure) while performing a job. This model can be used to identify a specific task/tasks producing excessive fatigue. The basic assumption behind this model is that jobs can be divided into simple tasks and that average energy expenditure for jobs can be predicted using the time duration of the jobs to estimate the energy expenditure of the tasks. Energy expenditure for simple tasks can be obtained from regression equations based on experimental data (Garg, Chaffin, and Herrin, 1978).

Energy expenditure for each task is based on the task variables which include object weight, frequency, technique, distance, and height while the individual variables include body weight and gender. The energy expenditure model was developed through a systematic collection of metabolic energy expenditure rate data for 28 different operations. Six healthy college students of ages between 18 to 22 years were used to conduct an experiment involving various experimental tasks. Over 540 oxygen intake measurements were taken. Loads and frequency were varied for each task. All experiments were performed for at least 10 minutes with a minimum of 20 minutes of rest between two successive experiments.

The mathematical model for the energy expenditure is as follows:

$$E_{job} = \frac{\sum_{i=1}^{n} E_P \times t_i + \sum_{j=1}^{m} \Delta E_{Tj}}{T} \qquad (2.5)$$

Where E_{job} = Average energy expenditure for the job (kcal/min); E_p = Energy expenditure for the i^{th} posture; t_i = time spent in the i^{th} posture; ΔE_{Tj} = net energy cost (over and above the maintenance of body posture) for the j^{th} task in the job (kcal); m = total number of tasks in the job; n = total number of posture considered; and T = time duration of the job (min) (Garg, Chaffin, and Herrin, 1978). In order to validate this model, 48 jobs were analyzed and resulted in a correlation of .95 and a coefficient of variation of 10%. Unfortunately, this model did not address issues such as training and environmental factors that could affect energy expenditure in manual material handling tasks. However, partitioning of a job into tasks also shows which tasks are more stress producing and could be used to balance the corresponding work load in each of the assembly cells (Garg, Chaffin, and Herrin, 1978).

The limitations that currently exist with the energy expenditure model include: (1) the model assumes additivity can be used to estimate the energy for higher levels of lift, (2) does not include the effect of object volume and angle of twist, and (3) tends to overestimate the metabolic energy requirement. However, these models can be used to balance the work load in various assembly cells.

2.6 EXPERIMENTAL/PSYCHOPHYSICAL APPROACH

The science of psychophysics can be used to identify the relationship between a subject's psychological states and a variation in physical stimulus. These variations are monitored and assessed through the subjects' responses to varying tasks. Experiments are carried out by attaching various sensors to the human body and reading the human reaction through specialized equipments such as computers and their LCD display. This display can be in an analog or digital mode depending on the nature of experiment to be conducted.

However, psychophysical methods work better with physiological measures such as heart rate, in order to observe how the activity of specific areas in the brain is correlated with observers' performance as a function of the stimulation (UCL, 2005).

2.6.1 PSYCHOPHYSICS AND INJURY ANALYSES

The principle of psychophysics has been used to analyze upper extremity cumulative trauma disorder. The main purpose is to examine different combinations of repetitive upper extremity work using already established psychophysical methods to determine design recommendations for various tasks involving the upper body. An assembly task where a worker transfers a part from a storage bin with a pneumatic tool to another larger part was used as an experimental study. Using this same approach, twenty-four experienced industrial workers were used for the experiment to address this problem related to upper body repetitive injuries (Krawczyk et al., 1993). However, this research was not very exhaustive. The 24 workers were right handed, hence making it difficult to prove the validity of the research for left handed workers. Moreover, the findings of the research cannot be used for future assembly line re-design as only right handed workers will benefit from the findings and there could also be a conflict if left handed workers were to be used in the same assembly cell. Also, the perceived exertion (VAS) rating provided by the subjects was based on a subjective measurement and could vary with respect to subject's perception of pain or discomfort. Conclusively, through the research, we were able to observe that gender was not a significant factor in the acquisition of upper body repetitive disorder.

A research was also carried out to establish acceptable impact severity for an automotive installation plant. This research was based on the fact that most assembly line operations involve the use of the hand which experiences a high level of vibrations and force during impact. Potvin et al. (2000) recognized the need to identify the safe level of each body part. He stated that the possibility to quantify the force, frequency, and limb posture does not in any way guaranty the ability to quantify their safe level. He used the principles of psychophysics to estimate acceptable loads under a variety of force load, time, frequency, and posture. In his experiment, he discovered that both skill and gender had significant effects on resistance setting which is used to measure the level of difficulty involved with the impact plate (Potvin et al., 2000). It was also discovered that the location of the impact surface relative to the body has no influence on the acceptable impact severity as measured while keeping force and acceleration as independent variables. The method used in conducting this research is very good as both skilled and unskilled workers were used during the experimental phase (Potvin et al., 2000). However, a major shortcoming was the inability to conduct these experiments for equal numbers of skilled and unskilled workers. Finally, these results at the time the experiment was conducted acted as a support to previous research conducted by Snook (1978) and NIOSH (1981) which presented at that time only an acceptable level for exposure to work loads. This work hence provided a limit for peak force and peak impulse prior to the revised NIOSH equation 1991 (Potvin et al., 2000).

Snook and Ciriello (1991) used a psychophysical method to determine the maximum acceptable weights and forces for various lifting, lowering, pushing, pulling and carrying tasks (Snook and Ciriello, 1991). The liberty mutual tables also provide valuable data for the identification of certain percentile population accommodated within a particular plant design (Liberty Mutual Group, 2004). Ayub et al. (1998) was able to provide similar guidelines. Snook et al. (1995, 1997) also used the psychophysical approach to set guidelines for various exertions involving repetitive wrist flexion, extension, and wrist ulner deviation. In their conclusion, they accepted the psychophysical approach as a valid technique for establishing acceptable exposure limits and that these limits are sensitive to changes in motion, frequency, time, and the nature of grip. Based on these previous research findings, Potvin et al. (2000) decided to establish the acceptable impact severity level for a re-occurring task that involves the door trim panel installation while considering the acceptable impact severity and the relative effect of impact frequency on the acceptable impact severity. Various times ranging from 2 mins to 8 mins were considered. The results of the experiment were used to create the acceptable limit for peak force and force impulse across frequencies ranging from 2 impacts/min to 8 impacts/min (Potvin et al., 2000). By using this approach, certain relationships were established between gender and skill on factors such as resistance, and hand acceleration variables. For high peak forces, load rates, impulses, and lower time-peak, the male subjects demonstrated the ability to accept higher peak forces, impulses and load rates and lower time to peak than the female subjects (Potvin et al., 2000). Hence, this can act as a convenient data for ergonomic analyses that involves designs for both male and female subjects.

2.6.2 INJURY ANALYSES DURING LINE OPTIMIZATION

An ergonomic analysis on the bucket brigade manufacturing method was used to identify potential physiological and biomechanical risk factors for cumulative trauma disorders and aims at establishing an operator based limiting design criterion. In the bucket brigade method, workers are subjected to varying workload, hence making it possible for some workers to be exposed to a grater risk of musculoskeletal disease.

Workers are arranged from the slowest to the fastest. The slowest worker is made to take the first position in the assembly line with progressively faster workers placed in order along the line until the fastest worker is located in the last position (Quintina and Skelton, 2001). The ordering of workers was found to eliminate blockages caused by variations in operator speed. This method is self balancing and makes the work on the line continuous and therefore leaving little or no recovery time. This characteristic could be injurious to workers health and could also lead to the production of poor quality products due to the increased physical demand associated with the process and which can be verified from the findings of previous studies (Emodi et al., 2007).

Hence on the bucket brigade line, two basic measurements known as cinematography and heart rate were used in obtaining the experimental readings on the human body while carrying out these experiments (Quintina and Skelton, 2001). Cinematography was used to establish a definition of the range of motion of various body segments for each of the subjects studied while heart rate monitoring was a technique used to measure the workers heart rates while carrying out their various tasks. To achieve the first step (cinematography), markers were placed at different locations of a test subject's body. Each of the operators was then captured on video in order to obtain certain angles of interest. Heart rate measurements are obtained using polar heart rate monitor that measure their minute to minute heart rate and also established energy expedition for their daily activities.

The final results of this experiment show that the last operator experienced a large increase in heart rate when he switched form the traditional line to the bucket brigade line due to the increased responsibility placed on the last worker. However, in as much as this has a negative effect on the health of the worker, it has also increased the turn over at that point in the line (Quintina and Skelton, 2001). Hence, the author's intension should be to strike a balance between productivity and workers safety. Using the polar heart rate monitor remains a valid psychophysical approach for measuring the workers energy expenditure.

2.6.3 INJURY IN RELATION TO WORKSTATION SPEED AND DESIGN

The forces produced at the fingers while intercepting moving cylinders in a simulated assembly line were obtained through previous studies. The aim of this is to ensure a safe work environment through the understanding of the assembly line performance. Participants were made to grasp heavy, medium and light cylinders that were instrumented with force/torque transducers moving at slow, medium and fast velocities along a moving track. Hence, the results aimed at contributing to both human safety and output. They found that mass was a major contributing factor to torque and grip force. There was no significant effect of a cylinder velocity on grip force. Finally, the results of their analyses show that the momentum of a moving target will influence the forces generated at fingers during grasping. This research was also able to discover that the increase in assembly line speed will not only increase overall production, but will also increase the risk of work injury (Dubrowski and Carnaham, 2004). In order to avoid injuries, assembly line speed can be manipulated while considering the mass of the objects. If the masses are overbearing, special devices can be used instead. A multiple regression analysis was used to relate subjects to cylinder masses, cylinder velocities, linear momentum, and peak load. However, the volunteers used for this study are all right hand users. This might not have any significant effect on the values obtained but may affect the future designs if inferences are drawn based on factors such as reach.

An investigation was conducted to discover the effect of stool height and holding time on postural load of squatting postures (Chung et al., 2003). This is due to the previous finding that prolonged squatting without any supporting tool will gradually result in musculoskeletal injuries. An experimental based approach was used to achieve this aim. Each of the 8 subjects used in the experiment were made to rate discomfort for the whole body, the lower back, the upper and lower legs while holding the squatting posture for a total of 16 minutes over a 2 minute interval. This rating was done using a subjective approach. Four different stool heights were used as independent variables while the subjects were made to simulate welding positions. This study used statistical methods to prove that stools of proper heights are needed to safely perform jobs requiring prolonged postures. Also, a major part of this discomfort was experienced on the lower leg. However, the postures here are only limited to symmetrical postures. Asymmetric and other varying postures are experienced in actual production environments (Chung et al., 2003). There is need for an objective workload measure to be included in order to support the findings of this study. Such measurements could include psychophysical measures like heart rate monitoring using an electromyograph.

Certain loads are best operated using automated mechanisms. The ergonomic and productivity impacts of partial automation strategies in the electronics industry have already been investigated. The total repetitive assembly work at the system level was reduced by 34% through partial automation. Automation of the transportation reduced the transport labor by 63% (Neumann et al., 2002). This research came with the conclusion that automation reduced operator's physical exposure to repetitive assembly task operations. However, it was also discovered that automation led to increased intensity, productivity, monotony, and WMSD risk for other remaining manual assembly work. Hence, automation does not necessarily improve the remaining manual workstations. The authors then concluded that ergonomic considerations in early design stage can improve both safety and productivity. This will involve incorporating or neglecting automation for actual assembly line designs (Neumann et al., 2002). However, very limited sample size was used in this experiment making it difficult to arrive at a reasonable statistical conclusion. The qualitative descriptions used in place of quantitative measurements do not have any scientific basis for actual performance analyses as individual assessments vary with respect to various factors. Hence, the results of this research may not be very helpful for other assembly plants but however suggests a trend for future analytical procedures.

Earlier study conducted in the car assembly industry has found the negative effects of ergonomics problems on workmanship and product quality (Eklund, 1995). Through subjective assessment, direct observation method and the use of archival data, a study was conducted to improve and optimize the Manual Component Insertion (MCI) lines in a Printed Circuit Assembly (PCA) factory. This study proved through an experimental approach the effect of ergonomics considerations when applied in a MCI line. This research however has its own limitations as no experiment was conducted to find the most appropriate insertion sequence and component bin arrangement. This is still a problem as the researchers improved the productivity of this plant through decreasing line down time. Reducing line downtimes partly removes unscheduled breaks usually observed by the operators and will also increase the risk of injuries and fatigue (Yeow and Sen, 2006). In consideration to this study, a major problem which the authors neither considered nor observed was the need to specify the dimensions of the facilities in the workspace such as stool height and work bench height and relate it to the height of the operators carrying out the experiment. Hence, the adjustment of the bin height should have a relationship with the height of the operator, and the height of the work bench. Also, the authors did not consider the anthropometry of the assembly line workers. This questions the validity of this research finding in terms of human safety issues.

2.6.4 STRENGTH AND POSTURAL DATABASE

In addition to the existing data base available for injury analyses, certain researchers have continued to carry out experiments aimed at obtaining additional database information. One of such experiments involve the determination of the shoulder flexion torque strength in young men and women (Koski and McGill, 1994) Peak static strengths were analyzed for 0º and 45º angles. Further experimental analyses were also conducted under a speed of 50º/sec on the dynamic shoulder flexion torque using a dynamometer (Koski and McGill, 1994). Because this research made use of male and female subjects in its analyses, the effect of gender on static and dynamic strength showed that male subjects had two times the strength of the female subjects. However, these experiments did not address the issue of age as a factor which could affect the static or dynamic strength. It was also observed that the experiment can only be used for younger population about the mean age of 22 years (Koski and McGill, 1994). A good number of assembly workers fall beyond this age bracket.

Also, it was obvious that the angular positions considered in the analyses were 0º and 45º. Does it mean there is no strength variation within other angular positions? This question was answered by a study conducted to obtain the mean and standard deviation of strengths across various joints (Chaffin and Anderson, 1991). They were able to discover a large variation of strength as joint angle increases from 0º to 90º. A set of equations known as Mean Joint Moment Strength Prediction equations were derived to be used in the calculation of strength at various angular positions of the body segments using factors such as gender, percentile, posture, and mass of segments as input parameters. However, just like the previous experiment by Koski and McGill (1994), the issue of age was still not addressed in this study.

Further studies have been carried out to discover the influence of age, body height, and weight on isometric shoulder muscle strength (Lannersten et al., 1993). The results show no significant influence of age on the flexors, abductors, and external rotators between the ages of 19 to 65 for females, while older men showed a significant lower difference in shoulder flexion strength than younger men. The most valuable information obtained from this experiment shows no significant difference in muscular strength between the ages of 19 to 44 years in any of the groups. Is this enough reason to neglect the issue of age in other experimental analyses based on the assumption that many assembly workers do not exceed the age of 44? The answer is no as many assembly line workers still fall beyond this age bracket and need to be considered. The other valuable findings of this analyses include: (1) Men are significantly stronger than women, (2) A weak correlation was discovered between body height and shoulder flexion strength, (3) A weak relationship was also discovered between body height and abduction/external rotation for male subjects, (4) A strong correlation was discovered between flexor strength and body weight (Lannersten et al., 1993). The database obtained from the research is currently being used in many ergonomic software packages.

Analysts believe that special equipments can be used to collect such information relating to injuries from subjects directly using a more objective experimental approach. However, this information will still need to be presented in a database for future use. One of such is the Lumber Motion Monitor (LLM) used to assess the effect of dynamic movements of the back (Marras et al., 1999). LLM is a tri-axial electrogoniometer that acts as an exoskeleton on the lumber spine when positioned and fastened on the back. This could be used to monitor subjects in similar work environments in order to obtain valuable data used in monitoring the positions and reactions of the lumber spine during various operations. After this is done, a computational analysis is then used to asses the risk probability across subjects carrying out similar tasks (Marras et al., 1999). This approach, just like most experimental methods, will obstruct the current production and also consume a lot of time and energy. However, the main benefit of the experimental technique is the ability to use the information generated to create a database for future analyses.

2.6.5 DATABASES FOR POSTURAL ANALYSES

In addition to these databases that currently address the issues on strength; some additional databases do exist in current literature in form of tables or charts for postural analyses. Some of these include the MITAL tables, the Snook and Ciriello tables, the Rapid Upper Limb Assessment (RULA), and the Rapid Entire Body Assessment (REBA). The Snook and Ciriello table allows the user to find the maximum acceptable weight for a particular task while putting into consideration factors such as frequency, population, and time. This database was generated using an experimental approach consisting of different studies over a period of 30 years. The subjects are made to modify their own feeling of exertion, hence making it possible to adjust the weights of the objects being manipulated. The maximum acceptable weight is the weight that is acceptable to the worker without feelings of exertion. Dynamic activities were used to make the readings as realistic as possible. The subjects were also made to lift weights by starting with either a very light weight or a very heavy weight. The current 1991 tables are based on a sample size of 119 participants (68 males, 51 females).

However, just like most things in nature, there are a few limitations associated with the Snook and Ciriello tables. These limitations include: (1) the reliance of psychophysics on individual assessment, (2) data from Snook and Ciriello tables for very high frequency tasks are higher than the recommended metabolic criteria which should be the basis for measurement, (3) Snook tables do not account for the bending and twist motions that are experienced during lifting operations, (4) The recommended biomechanical criteria at the maximum acceptable load are less than the maximum acceptable loads from Snook tables, (5) Snook tables did not put factors such as coupling/grip characteristics, duration of the job/task, the load asymmetry, the load placement clearance, the heat stress, and the limited headroom when establishing maximum acceptable weights. These unidentified factors could affect the results obtained on maximum acceptable weights for material handling tasks (Snook and Ciriello, 1991).

MITAL tables use the same population and database as Snook and Ciriello tables. However, the values obtained in the MITAL table can be adjusted for accommodate various biomechanical, physiological, and epidemiological criteria. The database can also be modified to accommodate various factors that may affect the maximum acceptable weight of industrial workers. This is done to ensure a realistic simulation and can be obtained through the introduction of multipliers for the adjustment of the following seven factors: (1) work duration, (2) limited headroom (spatial restraint), (3) asymmetrical lifting, (4) load asymmetry, (5) couplings (grip characteristic), (6) load placement clearance, and (7) heat stress (Mital et al., 1993).

The MITAL tables are used for the evaluation and design of manual handling tasks such as lifting, lowering, pushing, pulling and carrying. The MITAL tables can also be used for one-handed horizontal lifting analysis, one-handed carrying, holding, and material handling in unusual postures. The MITAL table also has a variety of population percentiles such as 10th, 25th, 50th, 75th, and 90th percentiles. The table is gender specific and the primary purpose of any researcher should be to accommodate a high population percentile range. However, some limitations do exist with respect to the MITAL tables and these include: (1) psychophysical approach is subjective and could vary from subject to subject, (2) The criteria for biomechanical analyses have a limit of 3930 N for male and this is higher than the NIOSH recommended value of 3434 N, (3) regression equations was used to determine the upper limit of maximum acceptable weight of 27 kg for male, (4) this equation has an explained variance of 75% while the acceptable explained variance is 80%, (5) The NIOSH suggested limit of 25 kg is greater than the upper limit value or maximum acceptable weight of 27 kg.

Rapid Entire Body Assessment (REBA) is another technique used in analyzing the human posture for risk of musculoskeletal diseases resulting from work. This is achieved by considering posture/postures that result from critical tasks. Each region is assigned a postural score and finally, these scores are aligned in a table to get the final score of the analyses. The main body parts analyzed during postural analyses are the wrist, neck, upper arms, leg, lower arms, and trunk. Using the generic REBA analysis, almost the entire body is being analyzed unlike RULA analyses that analyzes only the upper body (Hignett and McAtamney, 2000)

The following outlines the various procedures used in carrying out a REBA analysis: (1) the REBA table is used to associate a score with the trunk, neck, and leg postures. These are classified as Group A posture(s). The same operation is repeated for the upper arms, lower arms, and wrist. These are classified as the Group B postures. Each of these operations could then be carried out for the left and right body sides. Adjustment notes are used for additional considerations; (2) Associate a score with factors such as load/force, and coupling factors, (3) Use table A to obtain the Group A postural score (trunk, neck, and leg) and Table B for Group B postural scores (upper arms, lower arms, and wrist); (4) Score A is the Group A score added to the load/force score while Score B is the Group B score added to the Coupling Score for each hand; (5) Score C is obtained from table C by obtaining the point of intersection of Score B in the rows and Score A in the columns; (6) The final score known as REBA score is the sum of the Score C and the Activity score; and (7) The decision table is then used to find the degree of risk. The tables used for this analysis can be found using the reference information provided by Hignett and McAtamney (2000).

2.7 COMPUTER GRAPHICS MODELING AND SIMULATION

A study has been conducted which outlined the advantage of simulation models over analytic models (Sheng-Jen, 2002). The following were identified as the advantages of simulation models over analytical models: (1) simulation models are often easier to apply than analytic models, (2) analytical models require more assumptions to operate thereby reducing the level of accuracy, and (3) there are limited numbers of system performance measures that can be provided through the use of analytical models. On the other hand, the following are the advantages of the analytical models over the simulation models (1) simulation models are costly to validate and construct, (2) an analytical model can be used as a simple and initial model, and (3) a simulation model could provide an early insight to the behavior of more complex systems (Sheng-Jen, 2002).

Computer aided modeling and simulation may incorporate mathematical modeling, and experimental data. These are embedded into a computer program and enhanced with visualizations to provide realistic analyses. Human modeling and simulation is the mathematical representation of human characteristics or behavior. These characteristics may include physical attributes such as size and shape, as well as physiological issues such as fatigue. However, human models operate exactly the way they are programmed and based on the various attributes assigned to them, hence making it very relevant to set up the study accurately and with a high level of precision. The next stage will involve the accurate selection of a population. This is currently existing in a number of databases such as: (1) 1988 ANSUR Gordon et al., 1988, (2) 1988-1994 NHANES III (US), (3) CPSC (children), (4) HQL (Japanese), and (5) KRISS (Korean).

After selecting an appropriate user population, it is then left to the analyst to create manikins that characterize the desired space or goals. There are a number of statistical methods for selecting and creating human manikins based on larger anthropometric data sets. The goal is to create manikins that are digital representations of the specific human population. These manikins are modified to get the exact posture using various functionalities in the software tool. Various analyses are then conducted and the results analyzed to ensure a safer work environment.

2.7.1 INJURY ANALYSES THROUGH MODELING AND SIMULATION

Various potentials of simulation modeling have already been outlined in works of different researchers. Some of the researchers recognized the importance of modeling and simulation of different systems under different work environments. They also stressed the importance of this approach in advance of the actual implementation in the work place (Fallon et al., 1986). A computer aided approach using Ergo Socio-technical tool has been used to address the issue of human factors while optimizing production. An ergo socio technical software tool with the Participative Simulation environment for Integral Manufacturing (PSIM) project was developed. The researchers intended to describe the concept of this Ergo Socio-technical tool while focusing on the ergonomic part. This tool was designed to take into consideration factors such as physical load, ergonomic hazards, mental load, process flow and socio-technics (Lingen et al., 2002).

The various procedures applied in the implementation of this tool involves: (1) defining the assembly site and setting up a work group, (2) collection of basic inputs, (3) evaluation of current situation on ergonomic aspects, (4) evaluation of current situation on socio-technical aspects, (5) generation of possible alternatives (improvements), and (6) evaluation of other alternatives.

The Ergo socio-technical tool was tested on the Volvo automobile company and at Finland post and the results show that the simulation tool is useful in evaluating and identifying problems relating to physical load, process flow, mental load, and safety.

The benefits of this tool are undisputable. However, its usability is limited only to experienced simulation engineers due to the complexity of the software. The task analyses part of this tool is accompanied by five different modules. One of which is a socio-technical module and the four ergonomic modules. The four ergonomic modules include: (1) a process flow evaluation, (2) a physical workload evaluation, (3) other health hazard module, and (4) a mental workload evaluation. Some of the parameters are estimated, hence making it difficult to get exact values for so many factors. Hence, the results of this tool need to be used as an approximate value and not as an exact value.

A typical assembly line was used to demonstrate that a simulation and analytic modeling technique can be used as an effective tool for designing assembly lines. Issues addressing the optimal buffer size/locations and production environments are considered in order to maximize production. A simulation model was used to evaluate various production scheduling and to verify the number of safety kambans needed for each buffer. This model was used in the illustration of various methods needed for optimization. However, the models generated by the authors do not consider human capabilities in carrying out the various operations (Sheng-Jen, 2002).

2.7.2 CAD MODELING USING COMPUTER MANIKINS

Computer manikins have been used to evaluate the ergonomics of assembly tasks. Problems associated with the use of simulation to validate assembly line operations were also identified. In a production line, final assembly was seen to have the greatest impact on the human body due to the high level of repetitive movements involved. Computer manikins were also used to assess factors such as fit, clearance, reach, and line of sight. Amongst other benefits, the use of computer manikins is faster and easier than experimental methods which involve a larger number of people (Dukic et al, 2002). In a different research, Sundin et al. (2002) mentioned that the use of computer manikins consumes lots of time. This contradicts the earlier assumption by Dukic et al. that computer manikin approach is faster and easier than experimental and analytical methods. Sundin et al. (2002) also pointed out some of the limitations designers face when using computer manikins. Such limitations include accepting awkward postures, and providing too little space for movement. In a way, using computer manikins is faster and safer for the population being monitored. The use of actual experiments seems to pose a great risk to the workers or subjects as lots of time is needed to set up real time experiment environments.

2.7.3 APPLICATION OF VARIOUS SIMULATION SOFTWARE PACKAGES

An evaluation was conducted on a method used to predict the physical demands of work postures, force, and repetivity. This method being evaluated is known as Ergo-Sam. The Ergo-Sam is a method based on SAM, a high level method time measurement system. However, the Ergo-Sam required two additional pieces of information for the analyses. They are: (1) The zone relative to the workers body in which the activity is either carried out or ends, (2) The weight of the objects handled or the force exerted in the activity (Christmansson et al., 2000).

The analysis made was from video recordings and details were not addressed regarding the load levels. The results of their experiment showed that Ergo-Sam can be used to predict physical stress for the workers. However, these experimental analyses did not consider stressful positions for the hand, wrist, and neck nor did it put into consideration mental stress. However, the predictions made by Ergo-Sam are based on a database of expert judgments and limits for posture, force and repetivity. This is the same approach used by most tools used in postural and upper limb analyses. The Ergo-Sam is by no doubt a useful tool. However, there are other important factors which were not considered. These include the race and anthropometry of the assembly line workers. The inability to consider these two factors makes it difficult to apply the findings of Ergo-Sam in different environments. Also, the researchers were able to identify that Ergo-Sam will require a little extra time. This extra time is needed to mimic the exact postures and movements of the manikins.

In the Ergo-Sam analyses made by Christmansson et al. (2000), a delicate assumption was made. They assumed that in a realistic planning situation, lifting devices would not apply. From previous assembly experience in a production plant, realistic planning can only take place if all components of the line are considered. These components include humans, machines, robots, manipulators, components, parts, and tools (weight). The negligence of any of these factors could cause a significant difference in the results of the Ergo-Sam analyses. Also, judgments based on weights of components should not vary with respect to individuals. Prior to a simulation or modeling analyses, a simple scale can be used to obtain the weights of existing components in the plant. There is need also for simulation scientists to have a detailed drawing or model of the components in order to understand such factors as reach and clash. The Ergo-Sam software on the other hand considered three main inputs: (1) work posture, (2) force, and (3) repetition.

The Delmia V5© software has an ergonomics bundle that addresses a wider range of input parameters than the other ergonomics software packages analyzed. Delmia V5© software incorporated human anthropometry, race, and gender in its environment. A wider range of results are made available through the use of this software for injury analyses. The output parameters include such details as L4-L5 moment, L4-L5 compression, body load, compression, axial twist compression, flex/ext compression, L4-L5 joint shear, abdominal force, abdominal pressure, ground reactions, maximum acceptable sustained force, and maximum acceptable initial force. These results are then automatically compared with existing standards already set in the software environment to determine the safety of a particular work condition. The Delmia V5© Software also has the capability of breaking down the results of RULA analyses into various body segments such as upper arm, fore arm, wrist, wrist twist, muscle, force/load, wrist and arm, neck, trunk, leg, and neck-trunk-leg. These segments are then assigned a color code that helps provide detailed information on the exact body part that could experience injuries. A common mistake made by Delmia and Ergo Sam is making posture the only variable that can be altered. Also, repetivity was also given only three levels therefore limiting its range of variation in actual work situations. Time consumed while building simulation and human postures is by no doubt large. However, the Delmia V5© software addresses issues of urgent concern and incorporates such equations and databases as NIOSH 1991, NIOSH 1981, and Snook and Ciriello guidelines.

A number of applications currently exist and are used in injury analyses. Some of these ergonomic software packages include: (1) Delmia V5©; (2) UGS' Jack Software; (3) ErgoIntelligence©; (4) Envision Ergo©; (5) ErgoEASER©; and (6) SafeWork©.

2.8 Injury Analyses Using Motion Tracking Systems

The Institute of Electrical and Electronics Engineers (IEEE) focuses on three major areas relating to the interpretation of human motion. These areas include motion analyses involving human body parts, monitoring of human motion using single or multiple cameras, and understanding human activities through image sequencing. Motion analyses of human body parts involves the low-level segmentation of the human body into segments connected by joints, and obtains the 3D mechanical structure of the human body using its 2D projections over a range of images (Aggarwal and Cai, 1997). Monitoring human motion using single cameras focuses on high-level processing, in which moving humans are tracked without observing various parts of the body structure. After the human image has been moved from one frame to another in image sequences, understanding human sequence becomes a natural and more accurate process that can then be analyzed (Aggarwal and Cai, 1997).

However, the monitoring of human motion has seen a new perspective in its use in the Motion Analysis Corporation (see Appendix C). Various institutions such as the National Research Council of Canada are currently adopting this new technology in solving industrial needs. The Evart motion tracking analyses adopts the use of eight different cameras to track the various trajectories on the human body. The subject in some case is made to wear a special suit that contains special equipments that can be sensed by the cameras. The interesting part of the Evart motion tracking system is its ability to connect with the Delmia software using a "Delmia Plug In" for direct transfer of the human models. This eliminates the amount of time initially consumed in building these human models. Hence, combining the use of these two systems will not only quicken computer aided ergonomic analyses but will also help provide valuable insight in the current work Cell being analyzed.

2.9 CONCLUSION

Amongst the various approaches used in injury analysis, the modeling and simulation based approach seems to be the fastest and safest approach. The experimental approach provides an insight and could be used to generate a database of information that can be applied in the modeling and simulation software packages. The experimental approach should not exceed this level of use as human health is put at risk when people are used for ergonomic analysis in the determination of extreme points of pain. The equations derived from the mathematical approach can further be improved to eliminate some underlying assumptions that can create errors in the results of the experiment. Some of these equations such as NIOSH could be modified to accept a wider range of repetitive values, and also accept an input for age factor.

Conclusively, a modeling and simulation based approach coupled with the motion tracking system would be the most effective approach for the ergonomic analysis of current assembly and production lines. Yet, there has not been a published work that gives a complete procedure for the analysis and evaluation of work injuries given an existing assembly line while considering the associated costs and effects. Until now, current literature has not addressed the issue of synthesis using computer aided approach. Hence, the need for Objective 1 ad Objective 2 presented in Chapter 1 of this thesis is justified.

from a given assembly line to the reporting of worker injuries quantitatively and associated with the cost that is incurred from the injury. This situation appears to justify the need of research objective 1 as presented in Chapter 1. Furthermore, the literature survey has not found any work on the synthesis of an assembly system towards the reduction of worker injuries, which therefore justifies the need of research objective 2.

CHAPTER 3: ASSEMBLY LINE

3.1 INTRODUCTION

A generic assembly line was used for this study. The assembly line under consideration specializes in the manufacturing of heavy plant machineries such as combines, and planters. This line has also been identified to be a potential risk due to the number of repetitive activities involved in production of the combines. The combines are used for harvesting grain. A vital product used in the manufacturing of combine harvesters is known as combine header. These combine headers act as the principle assembly that carries out the harvesting operation when attached to a tractor. However, so many cells make up the corn header assembly line. These cells are continually being challenged with human and machine operations. The assembly cells are planned in such a way that production is maintained at an optimal rate. The repetitive activities associated with optimizing production have affected the human operators adversely and in cases where the human operators are not considered during the optimization stage.

In this research, a few assembly cells are considered. These are symbolized with the letters A, B, C, and D. The activities carried out in other assembly cells are similar to those in the cells being analyzed. This makes it possible to apply the results of this research to other production lines in the plant. This section presents the various sequence of human, robot, and machine activities carried out in the plant.

3.2 COMBINE HEADER AND ROW UNIT

Fig 3.1a shows a photograph of combine header and its row units. In this particular case in Fig. 3.1a, the combine header consists of 8 row units. The combine header is the combination of the entire row units and is the principle harvesting machinery used by farmers worldwide. The major objective of this machine is to separate the grain from the chaff, thereby retaining only the harvested grain. This combine header is attached to the tractor which drives the entire equipment to achieve the objective of harvesting. The overhead cost of a 'combine' is very high. This has made it impossible for some farmers to independently own their own combines. Apart from the basic cost of production and materials, some other costs related to the 'combines' are not un-associated with some production problems such as injuries, human and material waste, cost, layout designs, etc.

FIG 3.1A: A COMBINE WITH 8 ROW UNITS

On the other hand, the row unit are units of assembly components put together to obtain the combine header. In the production line, various types and sizes of row units are produced. The sizes range from 6, 8, and 12 row units. However, the main steps used in the production processes for each row unit configuration is similar.

3.3 CURRENT PLANT LAYOUT

The current plant layout is designed in such a way that movement is limited from one Cell to the other. Various activities and techniques have been introduced into the production line to optimize production. Parts, machines, and components are arranged and planned in an orderly manner. Analytical methods were used by the industrial engineers to optimize the work layout. The manufacturing engineers provide the tools, parts, and also monitor the data management aspects of the production. Parts and products are transported from one cell to another using carts, conveyors, manipulators, and fork lifts.

The current production line can be described as a customized production line. Assembly parts are moved manually from one cell to another. Production can also be modified using this system to accommodate multiple product types and even possible expansion. The other type of assembly line which can be described as automated does not allow for such flexibilities. These lines are usually provided with automated conveyors and planned to carry out various operations at a specific time. This kind of automated and synchronous assembly operation can also be detrimental to human health.

The current layout for the production of the 'combine header' involves 14 different work cells. These can be classified using arbitrary representations such as A, S, P, P1, P2, P3, P4, P5, M1, M2, M3, M4, M5, and M6. These figures are used to differentiate the various cells analyzed. However, only work cells A, P1, P2, P3, P4, P5, are studied in this thesis research as these are the actual cells that carry out the assembly of the row units. Hence, we will be further analyzing the production of the row unit assembly as this was the principle assembly line identified for this study due to the presence of various repetitive operations that may lead to further risk of injuries.

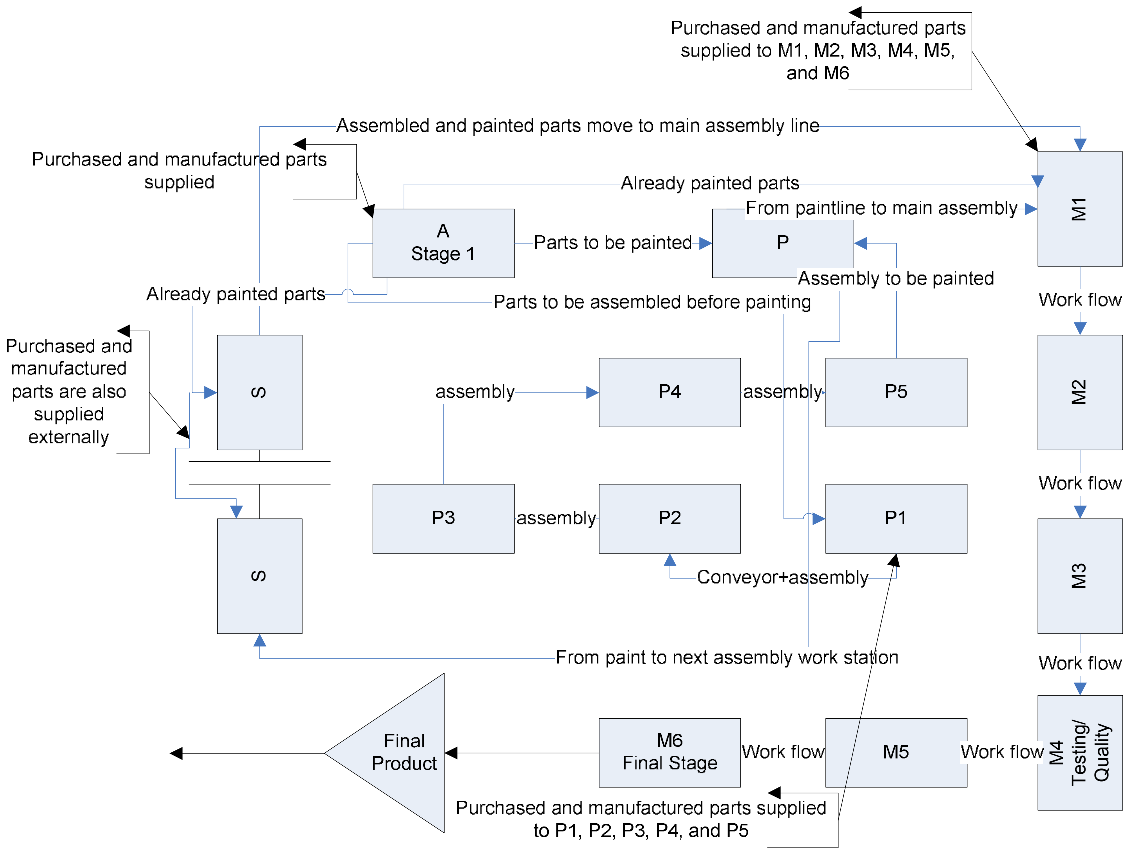

FIG. 3.1: ASSEMBLY-FLOWS SEQUENCE

As can be seen in Fig. 3.1, production starts from Cell A. The parts needed for this assembly line are either manufactured in the plant or ordered through a supplier. These parts are assembled and moved to assembly Cells S to P1-P6. The assemblies that do not need painting are moved directly to assembly Cell S while those assemblies that cannot be painted are moved to Cells P1 to P5 depending on where the exact assembly is needed. At Cell P5, the assembly is due to enter the paint line, P. Once the assembly leaves the paint line, it is transported using hangers and fork lifts to assembly Cell S. In this Cell, some other parts are supplied from other cells for production. Cell S completes the sub-assembly production of Product XYZ before being transported to assembly Cell M1 where the production of the higher level product (corn header, say Product Q) is commenced. The work flow is shown in Fig. 3.1. At M4, the corn header is tested to ensure quality production. Final assemblies that involve installation of plastics and other components are then carried out in Cell M5 and M6. The final Product Q is then moved outside the assembly Cell for shipping.

3.4 ASSEMBLY CELLS

Some of the procedures in the assembly operation can be classified as move, inspect, lock, assembly, and obtain. Some of these operations are carried out with the use of power tools, robots, manipulators, carts, etc. The process will outline the processes, the tools used, and the time of operation of each task carried out. Fig. 3.2a shows a typical assembly cell.

FIG 3.2A: A TYPICAL ASSEMBLY CELL

3.4.1 ASSEMBLY CELL A

The assembly Cell A shown in Fig. 3.2 is the first stage of the corn header assembly line. In this cell, various parts are put together to form basic assembly components. The assembled parts are then moved to Cell P1 in Fig. 3.3 (which is the next assembly cell in series) and other assembly cells in the plant where similar assembly products are needed. In some cases, the assembled parts that do not need to be painted are moved to the later stage of production while the rest are transported in series towards the paint line. Fig. 3.2 shows the various human, machines, and robot activities carried out in Cell A.

Amongst the several operations, a particular operation illustrated in Fig. 3.2 was identified for further ergonomic analysis. The particular operation identified in Fig. 3.2 is “Retrieve and lock (8.64 secs)”. This operation will need to be analyzed further using the Delmia V5© software package in order to evaluate its safety.

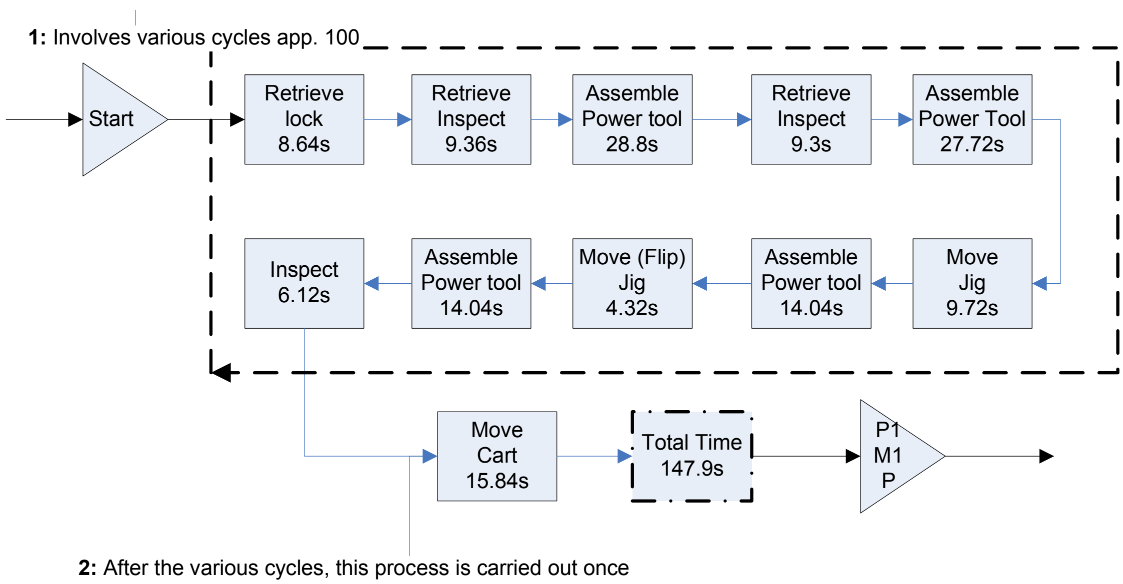

FIG. 3.2: CELL A

3.4.2 ASSEMBLY CELL P1

Cell P1 marks the first stage of primary assembly. Parts are supplied externally, while some other parts are transported from Cell A. The sequence is timed in such a way that at the end of this operation, Cell P2 is free to receive assemblies from Cell P1. It can be seen from Cell P1 that a lot of time is put into cutting a box strap. However, the primary purpose is to identify the operations that are detrimental to human health using a modeling and simulation based approach. Each of these operations is analyzed before modeling is commenced. Fig. 3.3 shows the various human/machine operations carried out in Cell P1. The time involved in each of these operations is included in the process flow diagram.

As an illustration, a posture related to the task "attach tape (20.88 secs)" is shown in Fig. 3.3a. The particular operation related to this posture poses an urgent concern in the plant due to the level of discomfort experienced while carrying out this task. However, a scientific method is needed to better understand the exact forces, stresses, and strain acting on the human body in this particular posture. Other sections that need to be analyzed in Fig. 3.3 include some postures in the" lift hoist (36.9 secs)" operation, and "assemble tool (115.1 secs)".

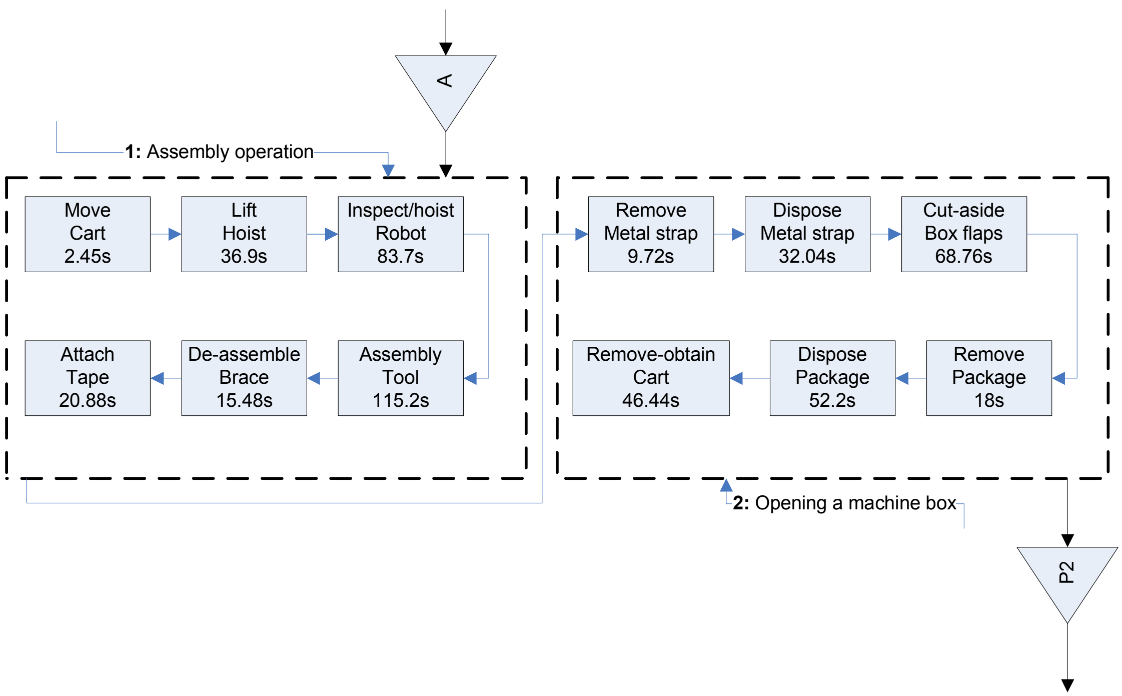

FIG. 3.3: CELL P1

FIG. 3.3A: HUMAN WORK POSTURE IN CELL P1

3.4.3 ASSEMBLY CELL P2

The assembly leaves Cell P1 to move to Cell P2. In Cell P2 shown in Fig. 3.4, more parts are added to the assembly. This particular cell is adjacent to Cell P1 as shown in Fig. 3.1. The main operations carried out in Cell P2 include; (1.) attach an object and advance forward, (2.) attach an object or component to the assembly, (3.) install a component, (4.) track and mark, (5.) move a cart, (6.) attaching a tag and (7.) signing off on the computer. Each of these operations is shown in Fig. 3.4. Some parts of these operations need to be considered based on the observations in the cells. Under very close observation, most of the operations involved in this Cell were considered safe and in no urgent need of further analysis. This can be seen through the results obtained on Fred 12 ("insert/grasp"), which is a sample posture in Cell 2.

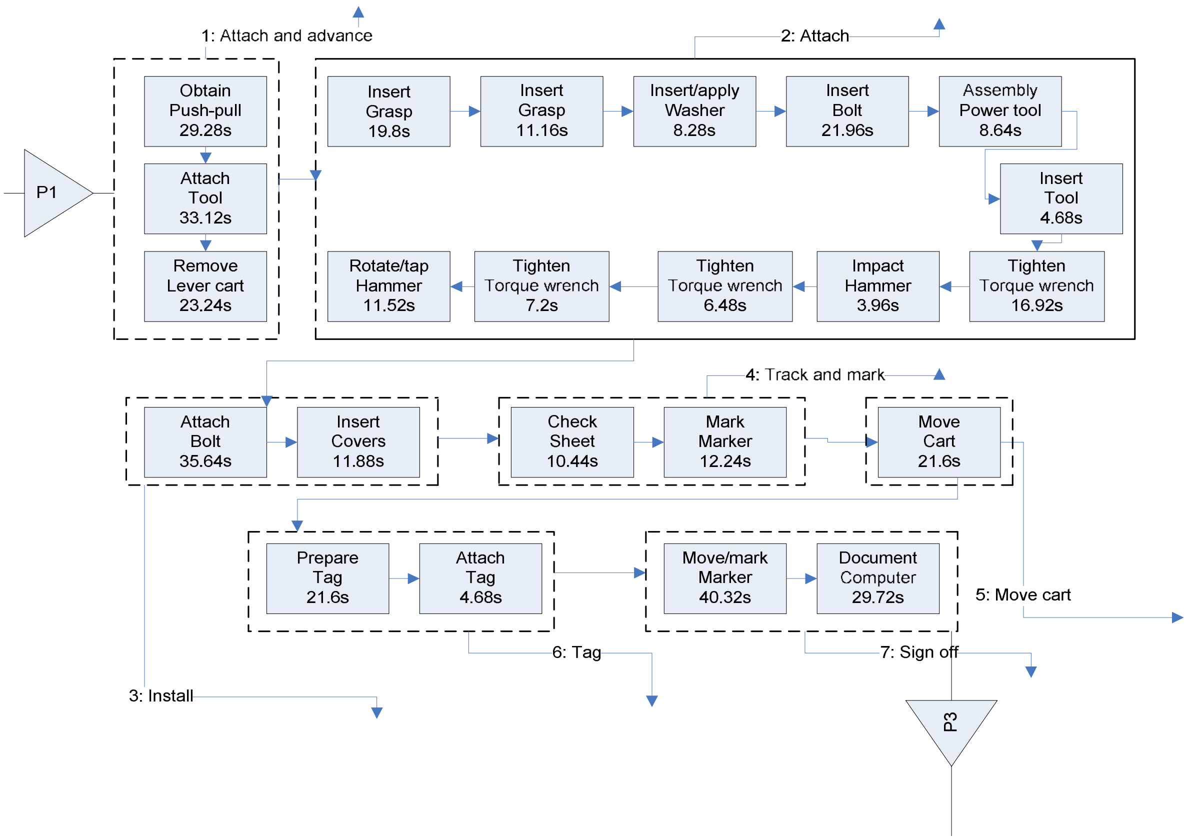

FIG. 3.4: CELL P2

3.4.4 ASSEMBLY CELL P3

The assembly leaves Cell P2 to move to Cell P3. In Cell P3, additional components are added before moving to Cell P4. Fig. 3.5 shows a sequence of operations carried out in Cell P3. Most of the processes in this Cell involve installation using hand and various other tools. The time involved in each of the operations are also presented. The main operations considered in this Cell include some postures in the following categories of operations; (1) Position/tighten (17.64 secs), (2) Inspect (10.44 secs), and (3) Move cart (12.24 secs).

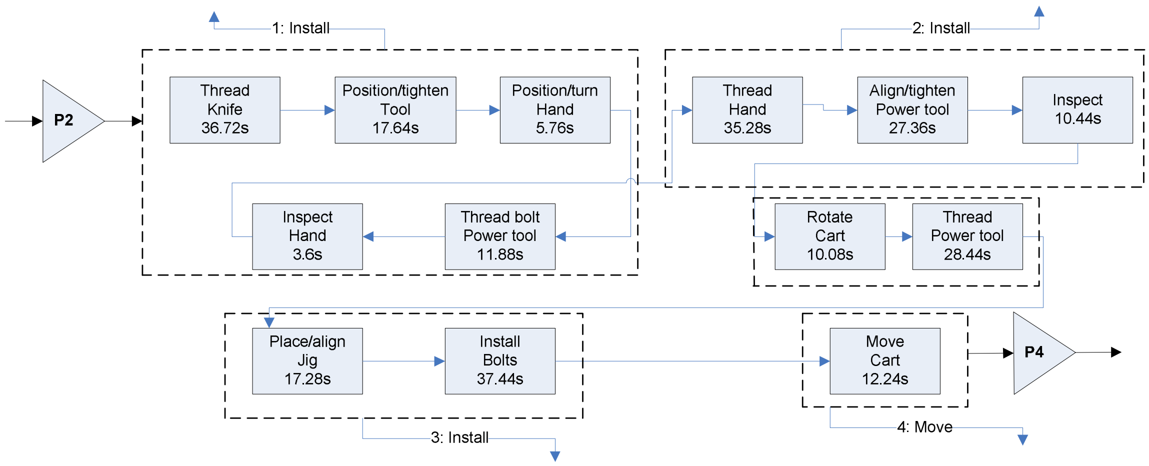

FIG. 3.5: CELL P3

3.4.5 ASSEMBLY CELL P4

From Cell P3, the assembly is moved to Cell P4. It can also be observed that all the operations are carried out by the assembly line workers and in most occasions, using hand tools. Various processes and time involved in the Cell P4 are illustrated in Fig. 3.6. The main operations studied in this category were work postures associated with; (1) Install/ Power tool (52.52 secs), and (2) Tighten/Power tool (17.28 secs).

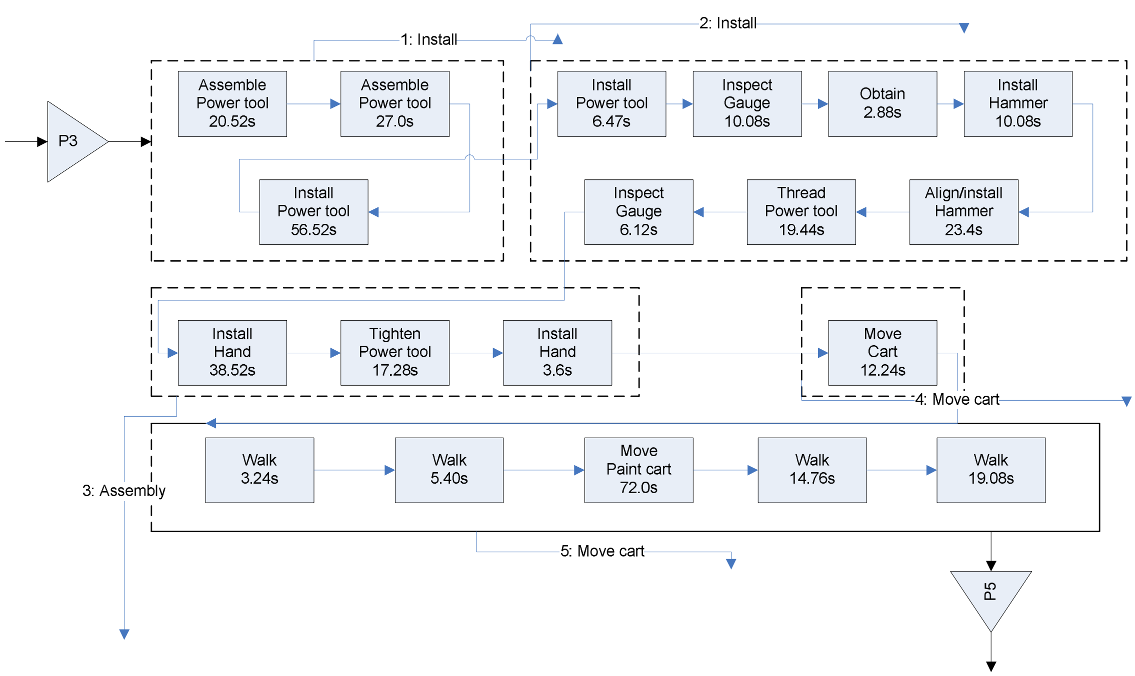

FIG. 3.6: CELL P4

3.4.6 Assembly Cell P5

From this stage, the assembly is moved to the paint line before further assembly is commenced on the product. This is a repetitive cycle and is carried out by the assembly line workers on an average 8 hr work day, 5 days a week. Fig. 3.7 illustrates the various processes taking place in Cell 5. These activities range from installation, to moving, walking, hoist operation, and retrieving. The main operations further analyzed in this Cell and as seen in Fig. 3.7 include; (1) Install/hand (6.48 secs), (2) Tighten/Power tool (19.44 secs), and (3) Move cart (16.56 secs).

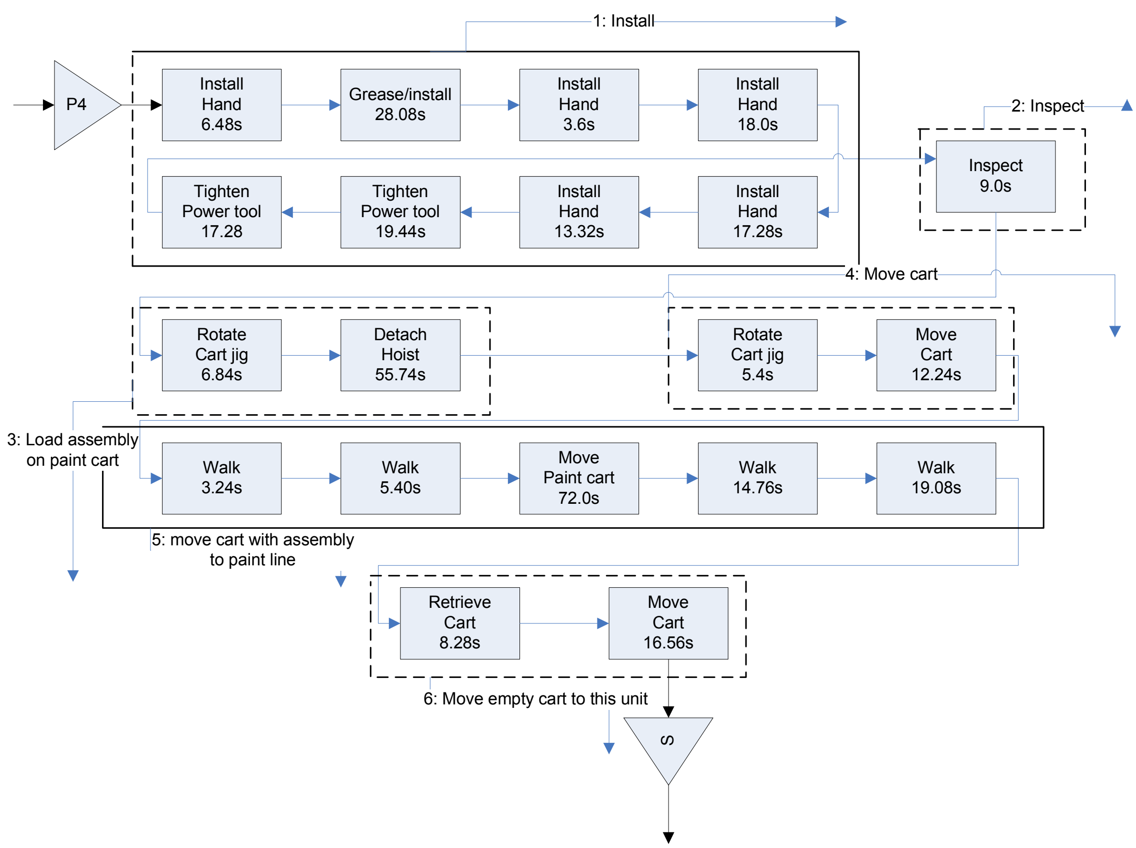

Fig. 3.7: Cell P5

3.5 Summary

The production line presented in this chapter has already been optimized for time. The workers in this line adhere to the highest level of safety procedure. Various parts and assemblies supplied from external sources as indicated in the diagrams.

However, the cells need to be further studied to verify and confirm the safety level associated with the various repetitive operations in the plant. The safety of the workers was not initially put into consideration during the time optimization stage. However, human safety should be a very important factor that needs to be considered during the optimization of any assembly line for improved productivity.

Hence, through this analysis, various aspects of the assembly cells were identified as potential risk. These conditions were already presented in Sections 3.4.1, 3.4.2, 3.4.3, 3.4.4, 3.4.5, and 3.4.6. Using a software package that incorporates various ergonomic guidelines, the various stresses and strains on the human body, while carrying out these operations can be calculated and evaluated. The various time information associated with the operations will act as an initial input variable during the CAD analysis.

CHAPTER 4: METHODOLOGY

4.1 INTRODUCTION

In this chapter, we present a methodology for the analysis and synthesis of an assembly system comprising of humans, machines, environment, and tools. The main goal of the analysis is to evaluate the current work situation for injuries as well as to obtain costs associated with possible injuries in the assembly line, while the goal of synthesis is to suggest and implement some changes while monitoring the effect of these changes on injuries and costs. All these are aimed at reducing or possibly eliminating repetitive injuries in production assembly lines.

Section 4.2 presents the general methodology for analysis, while Section 4.3 presents detailed procedural steps for the analysis. Section 4.4 presents the general methodology for synthesis. This chapter is then summarized in Section 4.5. Throughout the discussion, we use the example system as presented in Chapter 3 as an illustration of the discussions.

4.2 GENERAL METHODOLOGY FOR ANALYSIS

In order to reduce or possibly eliminate injuries in production assembly lines, two different methods were considered for this study. Each of the two methods accepts the input parameters such as weights, percentile, population, and frequency in order to obtain the desired output parameters such as RWL (Recommended Weigh Limits), LI (Lifting Index), maximum acceptable weights, etc. These output parameters are then studied to establish their relationship with injuries. The point at which injury is observed is identified as the point of anomaly from the ideal work situation. The ideal work situation was observed through experiments conducted while using various subjects in different work settings. These experiments were used to generate such algorithms and databases as NIOSH algorithm, Snook and Ciriello database, strength database, and RULA analysis. For the purpose of this study, two main broad methods of study were considered. The first method is classified as analytical and makes use of these database information and algorithms to obtain the necessary parameters that can be related to injuries. The second method uses a biomechanical model to study and obtain the necessary forces, moments, and compression on the human body needed for injury assessment. Each of these methods is discussed in Section 4.2.1 and Section 4.2.2 respectively.

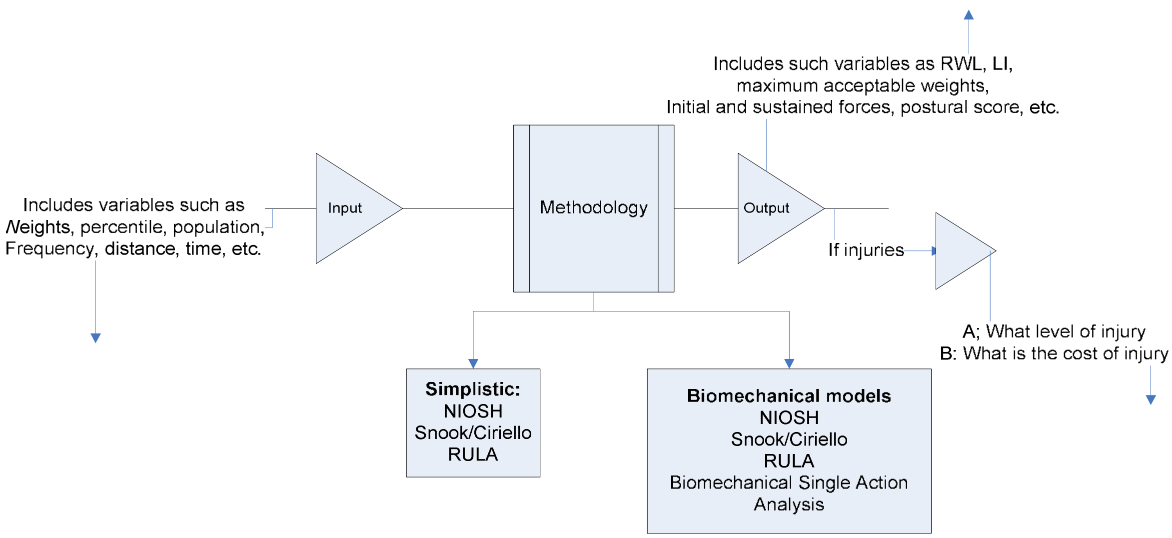

FIG. 4.1: REPRESENTATION OF THE CONCEPT ADOPTED IN THIS METHODOLOGY

4.2.1 ANALYTICAL APPROACH

The analytical approach as illustrated in Fig. 4.1 uses various algorithms and database information to study assembly operations such as carrying, lifting, pushing, and pulling. These models and algorithms present a basic standard for injury analysis. Some of these algorithms and database information considered in the analytical approach include the NIOSH algorithm, Snook and Ciriello equations, and RULA analysis.

The NIOSH equation is used to analyze and evaluate various lifting operations. The output obtained from this algorithm is the RWL and the LI. The RWL presents the recommended weight of load that nearly all healthy workers could lift over a period of time. On the hand, the LI is an estimate of the physical stress. These two parameters are vital in injury analysis. Firstly, a LI>1 shows an unsafe lifting operation. The LI is based on the ratio of the current weight of object being lifted and the recommended weight limit. Hence, LI is obtained through RWL and the object weight being lifted. To obtain the RWL, a formula presented by NIOSH is needed. This is shown in equation 2.1, while equation 2.2 presents the formula for the LI. The main variables required as input for these parameters include the horizontal component, vertical component, distance component, and coupling component. For example, if a NIOSH algorithm is to be carried out on an individual carrying out a lifting operation, the assembly worker is first captured on a video or camera. Various distances on the human body in the lifting posture such as the horizontal component (H), vertical location (V), distance component (D), coupling component (C), and asymmetric component (A) are used to obtain the various multipliers such as HM, DM, VM, AM, FM, and CM as was discussed in Section 2.5.1. These multipliers are then applied to equation 2.1 to obtain the RWL. The current load being lifted by the subject is then divided by RWL to obtain the LI as shown in equation 2.2. A lifting index >1 is identified as unsafe. Fig. 2.1 presents a pictorial representation of the various variables such as V, H, and D.

However, various limitations were observed in using the NIOSH algorithm for lifting analysis and these include:

1. The NIOSH algorithm does not consider the population of the human subjects under observation.
2. The output of the equation does not present the forces and moments on various distinct parts of the human body.

Another database considered is the Snook and Ciriello database. This database is used to analyze and evaluate such operations as lifting, lowering, pushing, pulling, and carrying. The tables were generated through psychophysical experiments carried out on human subjects performing various operations. Various input parameters include component weights, distances of lowering, lifting, and carrying, hand distance away from the body, and the task frequency. The output includes the initial and sustained forces for pushing and pulling operations, and the maximum acceptable weights for lifting, carrying, and lowering operations. The output is compared with the current plant operations such as the initial and sustained forces of pulling, and the current weights in order to identify injuries potential. For example, the Snook and Ciriello tables are used to carry out an analysis on any individual carrying out a lifting/lowering operation, push-pull operation, and carry operations using the following steps:

Step 1: Identify the actual percentile range intended to be accommodated in the current assembly line design. This is often used as 75^{th} percentile for male and 50^{th} percentile for female. The reason is to accommodate as many healthy people as possible in the design.

Step 2: Locate the appropriate Snook and Ciriello table: This can be for lift/lower, carry, or push/pull for either male of female genders.

Step 3: Trace the input parameters such as object width, lift or lower distance, population percentile, carry distance, and push-pull distance on the appropriate tables to obtain the maximum acceptable weights (for lifting/lowering/carrying) or the initial and sustained forces (for push/pull).

Step 4: Compare the output (e.g. maximum weights) with the current weights of parts or components currently being lifted, lowered, or carried in the assembly cell. If the current load in the plant is greater than the maximum acceptable weight, then, there is need for re-design. Also, in the case of pushing/pulling, if the initial and sustained forces obtained from the tables are less than what is attainable in the plant, then there is also need to modify the current pushing or pulling operation.

The Snook and Ciriello tables can be obtained from the Snook and Ciriello database or journals (Snook and Ciriello, 1991). However, the major limitation observed through the use of the Snook and Ciriello table is the absence of an option for population which has been found to have a significant effect on human performance.

RULA stands for Right Upper Limb Assessment. RULA analysis uses the principles of measuring angular deviations from ideal postures. Ideal postures were recognized through a series of experiments conducted on different body parts to identify the points of discomfort. Scores ranging from 1 to 7 were used to classify the angular deviations which are also used as injury levels. For instance, when carrying out a RULA analysis on a human subject in the system in Chapter 3, the various angular positions of the body segments such as upper arm, lower arms, and wrist are measured for both the right and left segments of the human body. These are used as input variables in addition to the amount of weight or load being manipulated by the human body. Scores present in the RULA table are then associated with the measured angles and a final value is presented. These values, which range from 1 to 7, are used as a measure of injury levels where '1' stands for the safest posture and '7' for the most unsafe posture. The RULA chart is presented in A4 as an additional illustration.

Various limitations associated with the RULA analysis are illustrated below:

1. The RULA chart does not consider such factors as anthropometry, population, and age as having an effect on the level of discomfort observed due to deviations from ideal postures.
2. Using the RULA chart, the values associated with the ideal posture cannot be modified to suit various work conditions.

From these, it can be observed that the analytical approach is associated with a lot of limitations. To eliminate these limitations, a different approach discussed in Section 4.2.2 was considered for this research.

4.2.2 BIOMECHANICAL MODEL APPROACH

This is a different method considered for the analysis and evaluation of injuries in the example assembly line discussed in Chapter 3 of this thesis. This method makes use of biomechanical models to evaluate current work situations. The biomechanical models are embedded in a software program known as Delmia V5©. The Delmia V5© is a program that includes biomechanical models knows as manikins. Individual segments on the human body are manipulated using direct kinematics. The kinematics options (forward or inverse) are initiated just by a single icon click in the Delmia V5© program. For each manikin in the Delmia V5©, the each of the body links can be manipulated in two or three degrees of freedom. The Delmia V5© software contains human models with as many as 99 independent links, segments, and ellipses. The various options in the Delmia V5© are described below:

1. Human Builder

This option uses a user interface to create human manikins with all the various segments and capabilities possessed by a real human. Usually, a percentile range is a major input variable in the human builder. In most occasions, the anthropometric value of 50th percentile for men or 75th percentile for female is used to ensure that a large population is accommodated in the analysis. The direct kinematics method is then used to manipulate various body segments in order to obtain the work posture under consideration. The manikin is also provided with vision capabilities.

The direct kinematics is a scientific method used in manipulating segments attached to joints. The human body segments are attached to various joint locations on the body. The human manikins are treated as a set of links attached to joints. The manikins are then manipulated just like robots using the direct kinematics method. This method is selected using the cursor and dragged on the appropriate body segment to obtain the desired angular positions of the segments. The internal structure of these models is provided with other characteristics obtained through various experiments. Such characteristics include vision, abdomen, muscles, back bones, etc.

2. Human Task simulation

This option is used to create and simulate various human activities. Some of these activities include walk, move, pick, place, etc. Relationships are created between manikin segments and the parts, tool or assemblies being manipulated in the work space.

3. Human activity analysis

This option is provided to help analyze the manikins and possibly evaluate the current work condition. The various analytical tools such as NIOSH, Snook and Ciriello, and RULA are used to perform the various injury analyses on a Delmia V5© user friendly interface.

4. Human posture analysis

This option in the Delmia V5© program is used to examine and provide various postural scores. Comfort and strength libraries can be modified to suit various individuals and their capabilities.

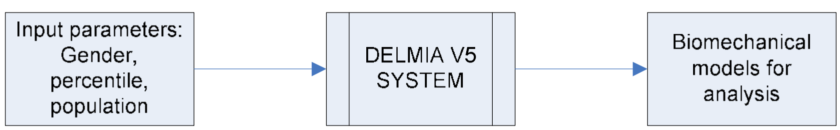

FIG. 4.3: FORMATION OF HUMAN BIOMECHANICAL MODEL

5. Human measurements editor

This option is used to provide customized manikins. This enables the accommodation of a wide range of humans during injury analysis irrespective of the percentile values. For instance, an unusually tall person that is skinny may not be accommodated by specifying just the 95th percentile. But with the human measurements editor, the exact size of the human being considered for the analysis can be obtained by inserting the exact measure of the various body segments. In the Delmia V5© human builder for instance, such input parameters as population, gender, and percentile are required to obtain a biomechanical model (manikin) for the analysis. This model will have a unique characteristic based on the different input information provided.

The various guidelines/options such as NIOSH, Snook and Ciriello, and RULA available in the human activity analysis option of Delmia V5© are used to conduct the various injury analyses on the manikin. Using the biomechanical model with the Delmia V5© while considering the posture of a human subject in the assembly line in Chapter 3, the human builder option is first used to create the appropriate human model given various input variables such as percentile, population, and gender. After the input variables are presented, the human measurement editor is then used to edit the obtained manikin model to suit the actual human posture under consideration by adjusting the size of various manikin segments. The actual human posture is viewed on the captured digital image which was obtained using a Sony digital camera.

The created manikin is then considered as the actual human needed for the analysis with various characteristics of a real human. Delmia V5© is then switched to the human builder where the direct kinematics option is used in adjusting various segments of the manikin body. Once the intended posture of the manikin is obtained, the human task simulation is used to associate various assembly models and operations with the manikin. In this option, the manikin is associated with walk, move, carry, climb, and several other operations that need to be considered. Also, assembly models created in other programs such as Pro-E and Solid works are imported into Delmia V5© under this option using various translators such as Pro-E translator for Pro-E files, and IGES translators for IGES files.

Delmia V5© is then switched to the human activity analysis option. In the human activity analysis, the various ergonomic tools such as NIOSH, RULA, Snook/Ciriello, and biomechanics single action analysis are applied on the manikin to observe various internal and external forces acting on the body. The NIOSH guideline which is one of the ergonomics tools/algorithms used within the Delmia V5© software environment is used for lift/lower analysis, while the Snook and

Ciriello guideline in Delmia V5© option is applied for push/pull, carry, and lift operations. The RULA analysis is used in analyzing the various work postures. The RULA analysis guideline in Delmia V5© presents the various postural scores used as injury levels of the current work posture. The injury levels for different body parts are also provided using the RULA guideline. Lift operations are studied with NIOSH guideline by presenting an indication of physical stress in form of the lifting index, while Snook/Ciriello guideline in Delmia V5© presents the maximum acceptable initial/sustained forces, and the maximum acceptable weights. The biomechanics single action analysis option in Delmia V5© presents the L4-L5 moment, L4-L5 compression, body load compression, axial twist compression, flex./ext. compression, L4/L5 joint shear, abdominal forces acting on the manikin, abdominal pressures, manikins ground reactions, spine limits, joint moment strength data, reaction forces, and manikins body segment positions in the work space.

The main limitations observed with the biomechanical model are:

1. The model building and simulation stage is time consuming especially when carried out without prior special training and experience.
2. Lack of compatibility between Pro-E Wildfire 2.0 assembly models and Delmia V5© for motion capture. Pro-E assembly models are popular and need to connect with Delmia V5©. This will eliminate the reproduction of already existing models in Delmia V5© environment.
3. The age factor has still not been addressed. However, the percentile classification was made for both the anthropometry and age thereby presenting the possibility of estimating a subject's age by presenting a low strength percentile.

The various advantages observed with the biomechanical models are:

1. The biomechanical models incorporate gender, percentile, population, and anthropometry which have been found to have a significant effect on injuries.
2. The models can be used to calculate the various angular positions of the body segments in contrast to physical measurements.

3. The biomechanical models also provide the forces, moments, and stress acting on various body parts such as on the L4-L5 disc on the human lower back
4. The human models can also be manipulated accurately through simple observation of motion capture on video or pictures.
5. The models can be used to study the field of view, and the reach in consideration to the actual work environment.
6. Biomechanical models embedded in Delmia V5© can be used to compute the various internal and external forces acting on body parts while carrying assembly operations.

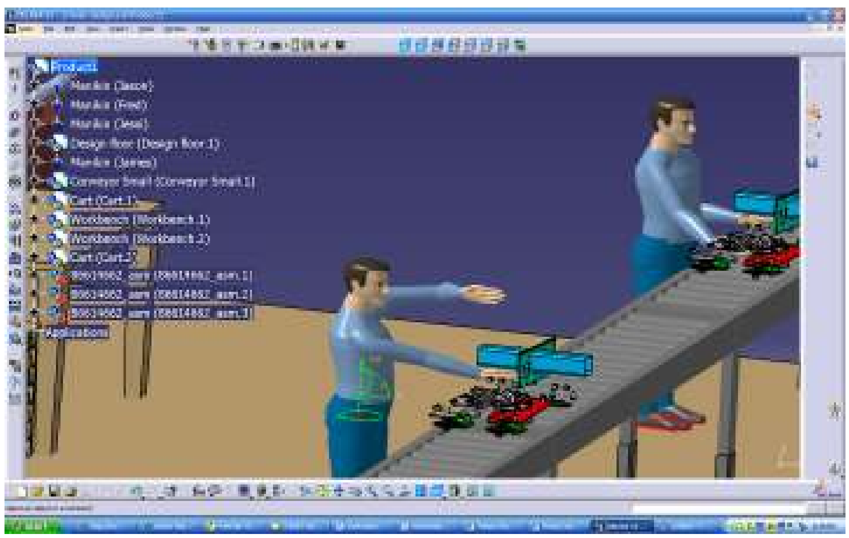

FIG. 4.4: DELMIA V5© SOFTWARE SCREEN CAPTURE

After various considerations which involve such factors as accuracy, usability, and effectiveness, on both the analytical method and the method of biomechanical model, we decided to use the method of biomechanical models for this study. This method will be carried out using the Delmia V5© bundle that has the various options described in this section. In as much as the Delmia V5© made use of the various mentioned algorithms as would be used in the analytical approach, the applicability in the Delmia V5© environment has incorporated various factors which helps improve the results of the experiment. Some of these involve the ability to manipulate these biomechanical models in for strength and anthropometry. Also, the RULA spreadsheet can be modified to suit particular work conditions of interest. Conclusively, this method seems to incorporate all the methods on one window, and in addition, internal properties associated with biomechanical models play a vital role in the final results of the analysis. This is not possible with the analytical approach.

4.2.3 COST ANALYSIS

After the injury analysis, cost information relating to repetitive injuries in production assembly lines will be used for cost analysis. The cost effects of possible injuries identified using the example system in Chapter 3 is then evaluated using the injury information from SWCB. The costs are analyzed using the statistical percentile range. The percentile breaks an arranged array of numbers into unequal intervals. Each of these intervals is associated with a particular level of injury. For instance, an injury level of 2 is assigned a cost on the 2^{nd} interval while an injury level of 7 is assigned a cost on the 7^{th} interval. The obtained data would need to be compared with the body classifications provided by RULA analysis. A leg injury observed through RULA analysis will be associated with costs on leg injuries obtained from SWCB. These comparisons will then be used to assign various costs to a particular type of injury. For instance, the cost of carpal tunnel disease presented by SWCB will be associated with a wrist injury calculated by Delmia V5©. Table 5.11 presents the injury classification relationship between Delmia V5© and SWCB. After the cost of injuries has been obtained, multiplicative index values are then associated with these costs to make it suitable for various 'classes' of assembly lines across the world. 'Classes' in this case refer to the safety level of the assembly line based on the recognized injury costs. This procedure will be followed by a design recommendation, implementation, and evaluation to understand the positive consequences of the re-design on injury and cost.

The various steps taken in this research are classified as methodology for analysis in Section 4.3, and methodology for synthesis in Section 4.4. The analysis explains the procedures taken for the analysis and evaluation of the example system in Chapter 3 while the synthesis evaluates the implementation of a new design and its effects on cost and injuries.

4.3 Procedure for analysis

The processes illustrated in this section show the steps that were taken to achieve the various objectives of this study.

Process 1: Acquiring necessary tools

The required tools should include repetitive injury costs from SWCB, digital cameras for motion capture, Delmia V5© simulation software and IGES/ Pro-E translators, and production plant just like the one discussed in Chapter 3.

Process 2: Capture human motion in an assembly line

Use digital cameras (Sony handyCam) to collect motion capture data from the production plant. This data includes all aspects of the human posture while carrying out various assembly operations.

Process 3: Study captured motion

Study human motion captured on video to obtain such parameters as operation time, frequency of operation, and angular positions of the body segments.

Process 4: Identify the various variables in an assembly cell

The aim of this identification is to understand the particular variable that either needs to be varied or kept constant during this study. These variables are classified as controlled variables, dependent variables, and independent variable.

(a) Controlled variables

These are the variables that are kept the same throughout the experiments. This will include such parameters as; (1) 50^{th} Percentile male or 75^{th} percentile female, (2) gender, (3) population of workers under consideration (Canadian work force), (4) work space dimensions; and (5) Component weights and dimensions.

(b) Independent variables

The main critical variable under consideration is the angular positions of the body segments which determine the human posture. Other independent variables include frequency of operation, duration, distance (of carry, push, pull, etc.) and initial and final lift/lower heights.

(c) Dependent variables

The dependent variables needed to obtain the measure of change observed due to the change in the independent variable(s) includes: (1) Lifting Index (LI), (2) Recommended Weight Limit (RWL), (3) Percentile population capable of carrying the current tasks of interest, and (4) Initial and sustained force.

Process 5: Formulate human models in Delmia V5©

Input gender, percentile (75^{th} percentile for male and 50th percentile for female), and population (Canadian) into Delmia V5© human builder environment. Then use the human measurements editor to edit the manikin to the exact required size. This does not affect the percentile strength of the manikin. Then use the direct kinematics option to adjust the various segments of the manikin model in order to match the observed posture(s) captured on video.

Process 6: Import component models into Delmia V5©

Use the Delmia task simulation option to import various assembly and part models into Delmia. Firstly, the assembly models in Pro-E are converted to IGES format in the Pro-E environment. Then convert the IGES models into Solid Works model files and then re-convert to IGES. The IGES translator is then used to import the Pro-E assembly models in IGES format into Delmia V5©.

Process 7: Build the process simulation

Use the human task simulation option in Delmia V5© to create a simulation of the various work activities using the assembly and part models in 3D, the manikin models, the plant environment and work space dimensions, and the various plant operations such as lift, pull, push, and carry. Stop the simulation at static postures and store in a special library for future analysis.

Process 8: Apply the NIOSH guideline

Use the human activity analysis option in Delmia V5© to apply the NIOSH algorithm on the biomechanical models. Provide such input parameters as frequency, duration, and component weights on the human models to obtain the RWL and the LI. For LI > 1, suggest a re-design. For LI < 1, the design is classed as safe.

Process 9: Apply the Snook and Ciriello guideline

Step 1: Push-pull analysis

Use the human activity analysis option in Delmia V5© and the Snook and Ciriello guideline to perform the push-pull analysis. Input such parameters as frequency, distance of push, and distance of pull. The system will provide the final results as the maximum acceptable initial and sustained forces.

Step 2: Carry analysis

Use the human activity analysis option in Delmia V5© and the Snook and Ciriello guideline to perform a carry analysis on the manikin models. Input such parameters as distance of carry, frequency of carry, and weight being carried. The result is presented as the maximum acceptable weight.

Step 3: Lift-lower analysis

Use the human activity analysis option in Delmia V5© and the Snook and Ciriello guideline to perform a lift lower analysis. Use input parameters such as initial lift height, final lift height, distance of lift, and weight being lifted to obtain the maximum acceptable lift weight.

Process 10: Perform postural analysis using the RULA guideline

In the human activity analysis option in Delmia V5©, select the RULA analysis guideline and apply it to the static postures saved in a special library during the simulation stage. Obtain the postural scores for both the postures and the individual body groups. Use the postural scores as injury levels.

Process 11: Perform biomechanics single action analysis

Use the human activity analysis option to obtain the internal forces, external forces, and moments acting on the manikin while carrying out the various activities. Use these forces to understand the effects of various work postures on the L4/L5 disc, and the numerical values of angular positions of all the body segments.

Process 12: Collect and analyze SWCB injury cost

Collect injury cost information from SWCB. Select the various costs associated with repetitive injury costs and save in a different excel file. Use the SPSS statistical software to group these costs using the percentile range. Group the costs based on individual body groups that have been associated between Delmia V5© and RULA.

Process 13: Cost analysis of current design

Associate the obtained costs from SWCB with the results of the analysis to obtain the current cost implication of the current plant design. Define the cost implication under two categories such as cost of injuries in different assembly cells, and injury cost on different body parts.

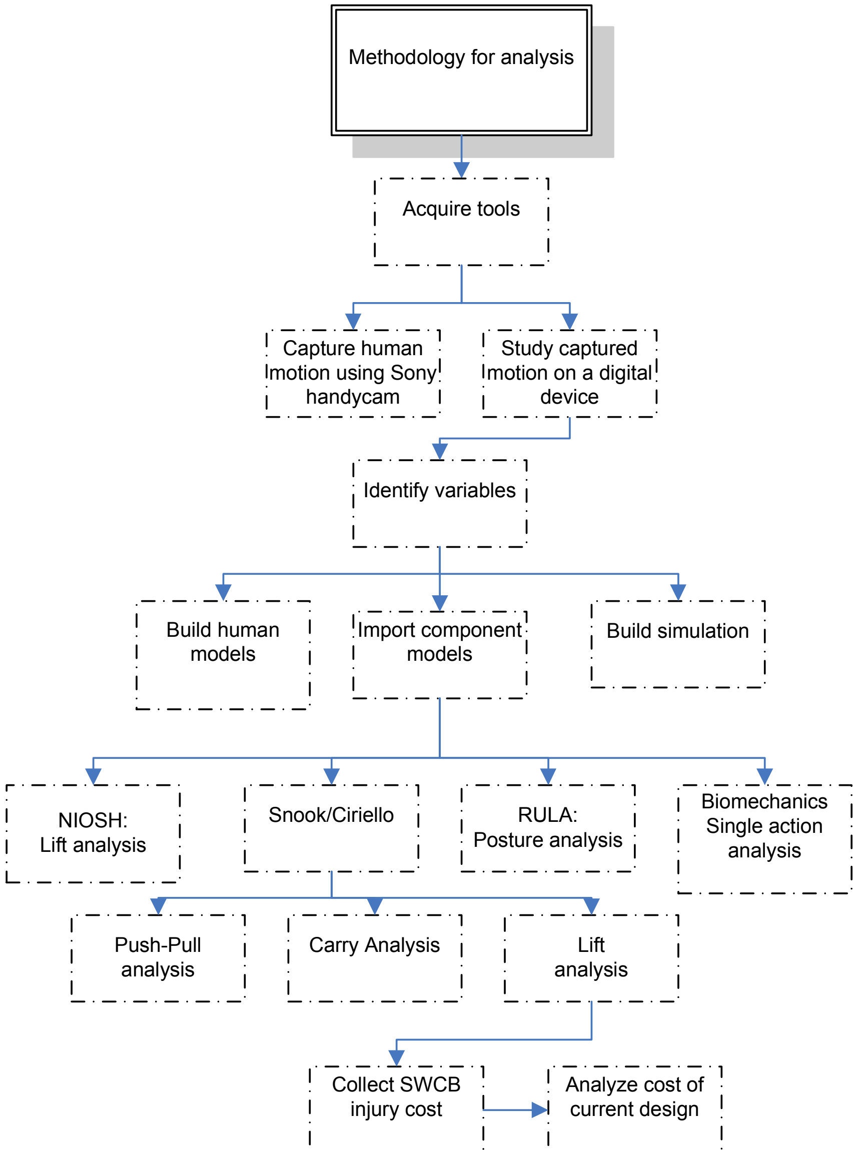

FIG. 4.5: DIAGRAMMATIC REPRESENTATION OF METHODOLOGY FOR ANALYSIS

4.4 SYNTHESIS

Synthesis is a process that stems from a need and ends at a solution that is supported to meet the need. Often, for achieving a particular need, there may be more than one solution, say 'n' number of solutions. The role of synthesis is to identify the best solutions amongst the 'n' of available solutions. However, while considering the possible solutions, there is need to put into consideration constraints in the system.

Hence, synthesis goes as far as discovering the best solution amongst the possible solutions while putting into consideration various constraints such as design costs and possible effects of design.

For a complex problem, a solution may not be apparent at first glance. In this case, the complex problem is synthesized into less complex segments. These less complex segments can then be addressed individually till the complex problem is finally solved.

Re-design is a synthesis process as it leads to improved designs to meet new requirements which are incremented from the existing requirements. In order to arrive at an improved design, the standard design should be compared with the existing design using a standard design knowledge base. This standard design knowledge base is generated based on previous experiments and experience that proves that these designs meet the safety requirements. In the case of this study, the new design requirements aim at reducing or possibly eliminating injuries that occur as a result of repetitive activities. Table 4.1 provides a database of standard ergonomic design principles which, if adhered to, would help reduce or possible eliminate repetitive injuries. This knowledge was proposed based on our experience in the example system in Chapter 3 and coupled with the insight generated from the literature reviews.

TABLE 4.1: DESIGN RECOMMENDATIONS

PROCESS	OBSERVATION	RECOMMENDATION
1	Eye level far above or far below the view location.	Alternate between standing and the use of adjustable stools to ensure a near horizontal eye level
2	Hand above shoulder level	Place tools, parts, and equipments in locations where they can be easily be accessible without having to raise the hands above the should level Paint line hangers for example should be reduced in height to eliminate this condition
3	Body twisting	Place tool on shelves in front of the workers to avoid twisting while obtaining them
4	Load weight	Do not lift loads greater than 20kg or the recommended weight limits obtained from CAD analysis. Do not lift long (>5 feet) and slender (< 2 inch thick) loads
5	Power tools	The use of power tools for various operations should be alternated between individuals on a daily basis to reduce risk of carpal tunnel.
6	Lunch/ coffee breaks	Coffee breaks, lunch breaks, and momentary rests should be ensured to reduce high work frequency and also introduce rest periods
7	Carry	Avoid carry operations as much as possible unless carrying a very small weight les than 10kg. Carry over short distances or use a trolley to carry for longer distances
8	Push-pull	The maximum initial and sustained forces of push or pull should not exceed any results obtained from the push-pull analysis using any generic ergonomics software Push all the time if possible and avoid pulling as much as possible
9	Lifting	Bend at the knee level and not at the waist while lifting or lowering Lift from a platform and not from ground level Lower loads from platforms about chest level Keep back straight while lifting or lowering

		Ensure that object size being lifted do not have a larger width than the body width.
10	Standing/Seating	Alternate standing and seating. Do not stand for more than 45 minutes at a stretch. Do not seat for long periods on a high stool (above knee level) to avoid build up of blood on the legs. For computer use in the plant, use of seats without arm rests should be avoided

4.5 PROCEDURE FOR SYNTHESIS

Synthesis in this case refers to re-design. The method of synthesis will be based on the various rules that can be used to control or eliminate injuries. Some of these rules are classified as basic rules of thumb. However, the scientific basis for these rules of thumb can be derived from the results of the previous analysis. Some other rules used in this synthesis are obtained from previous analytical procedures. Some other guidelines may be based on qualitative judgments made through the work experience in the assembly line.

During this period of synthesis, RULA guideline in Delmia V5© is first used to identify the poor work conditions in the plant. During this process, the exact body parts facing risk of injuries are identified through the RULA results. The proposed design guidelines in Table 4.1 is used to identify the right re-design process based on the results obtained from the RULA analysis. The newly re-designed process is then simulated in Delmia V5© environment. The human activity analysis option in the Delmia V5© is then used to carry out the specific ergonomic analysis to confirm the new postures are risk free. The cost information generated through the cost analysis is also used to identify the current cost of the newly re-designed process. The cost of the current design process is then compared with the previous cost on injuries. Fig. 4.6 shows the proposed steps for synthesis.

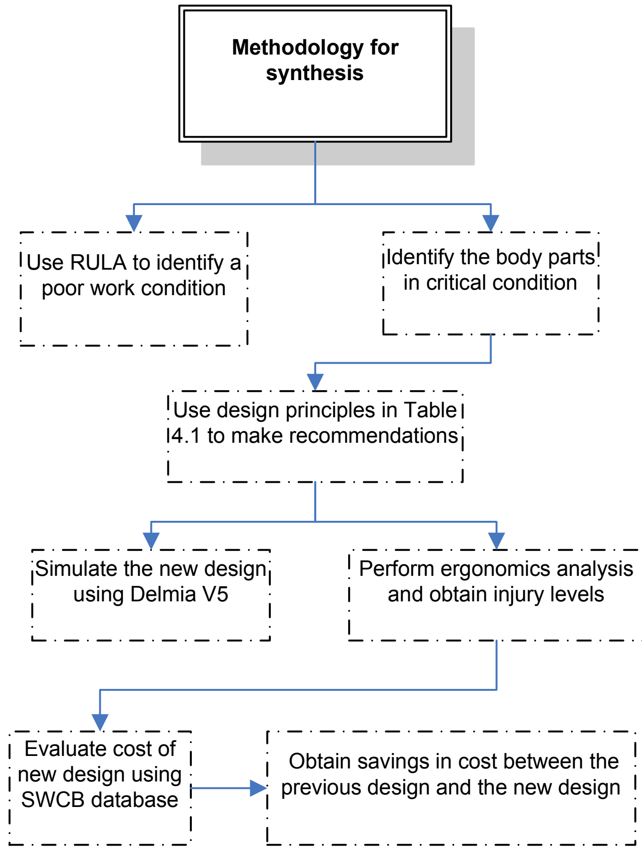

FIG. 4.6: DIAGRAMMATIC REPRESENTATION OF METHODOLOGY FOR SYNTHESIS

4.5.1 DESIGN IMPLEMENTATION

In order to identify the effects of some of these recommendations on cost, a current assembly line posture identified in the assembly line of Chapter 3 is used as a typical example. The current design where a worker carries out an activity by standing and trying to view an assembly part below chest level was modified by using Process 1 principle in Table 4.1. The worker was identified to be carrying out this operation under this particular posture at least 100 times in an 8 hr work day. The re-design is studied using the biomechanical models in Delmia V5© software and the cost is analyzed using the repetitive cost information obtained from SWCB database which was discussed in Section 4.4.

The following outlines the processes followed to achieve the re-design of a sample work condition.

Process 1: Identify a current work condition such as that in assembly line of Chapter 3 that involves a worker standing, twisting, and bending to fit a nut under an assembly.

Process 2: Identify body parts in critical postures and in this particular example, the work condition involves bending at the waist, the neck, and the shoulder level.

Process 3: Make a recommendation to use an adjustable stool to adjust eye level in order to avoid bending and twisting.

Process 4: Use the Delmia V5© software to analyze the current re-designed work condition following the same steps used in the analysis of Section 4.2.3. The new design is simulated and analyzed in Delmia V5© software environment.

Process 5: Analyze the injury cost effect of the current posture and compare it with the cost of the previous posture. Use injury levels obtained from RULA analysis for cost analysis and evaluation. Provide the results of the analysis as proof that the recommendation will have a positive beneficial effect on the assembly plant.

4.6 SUMMARY

The methodology presented in this work is not in any current literature. Current literatures have such algorithms as NIOSH, Snook and Ciriello, RULA, and REBA analysis. However, none of these literatures considered a collective analysis using all the guidelines in a computer aided environment.

Also, the use of the Delmia V5© software with the biomechanical models was very complex. Through this study, a new technique was used in importing Pro E Wildfire

2.0 models into Delmia V5©. This particular case was a major problem which was solved through collaboration with Delmia V5©. Also to improve the ease of use, process models were presented to act as a guideline for future ergonomic analysis.

In the current literature, the effect of repetitive injury cost and its association with Delmia V5© system has never been considered. This work was able to study the injury and cost effects on the assembly line in Chapter 3. The costs information was obtained from SWCB and analyzed using the SPSS statistical tool. These cost values were also associated with different human body parts. The final effects of these costs were evaluated with the cost information obtained after the re-design process.

The assembly line under consideration is a mixed product line. The production may change with respect to season. This work presents the various activities going on in a typical production plant. In addition, the injury cost information obtained from SWCB was analyzed in order to obtain injury information resulting from repetitive activities. Also, a rule of thumb will be presented to act as a guideline for future re-design.

CHAPTER 5: CASE STUDY

5.1 INTRODUCTION

This chapter presents the results of the analysis and synthesis conducted on the example system of Chapter 3. The biomechanical models approach in Delmia V5© was used in order to obtain various output information which could have been impossible with the analytical approach. The goal of this chapter is to demonstrate the application of the general methodology of Chapter 4 to the example system described in Chapter 3.

Section 5.2 presents the various injury level classifications, while Sections 5.3, 5.4, 5.5, 5.6, and 5.7 present the results of the case study particularly in the area of the RULA analysis, lift analysis, push-pull analysis, carry analysis, and biomechanical single action analysis respectively. Section 5.8 presents the results of the cost analysis, while Section 5.9 illustrates the results obtained as a result of the re-design conducted on a sample posture in the example system of Chapter 3. The summary of this chapter is presented in Section 5.10.

5.2 INJURY LEVEL CLASSIFICATION

The injury levels were classified by the RULA guideline which is further embedded in Delmia V5© for different body parts (Delmia V5©, 2005). These injury levels provide an estimate of the danger associated with various work postures under analysis.

The basic mode of the RULA analyses presented in the Delmia V5© program displays its final score in the form of colored zones and numerical values ranging from 1 to 7. RULA score 1-2 means that the subject is working in the most recommended posture with no potential risk of injury. RULA score 3-4 means that the subject is working in a posture that could present some risk of injury, and this could be as a result of a certain body parts positioned in an awkward position hence making it imperative to investigate and correct this posture. RULA score 5-6 means that the subject is working in a poor posture with a risk of injury, and the cause needs to be investigated and changed in the near future to prevent the occurrence of musculoskeletal injuries. RULA score 7-8 means that the subject is working in the worst posture with an immediate risk of injury, and the cause needs to be investigated and changed immediately to prevent the occurrence of an injury. Table A5.2 shows the color associated with various scores in the Delmia V5© software.

5.3 CASE STUDY: RULA ANALYSES

We applied the RULA analysis guideline in Delmia V5© on 15 different postures in the assembly line of Chapter 3. These postures were selected based on the observation made during the assembly work process carried out in the plant. Also from the video recording, some postures were identified as potential risk and this also necessitated the need to study in more details these postures. Some of the postures studies occur several times in different other cells in the plant, however, we intend to study each individual cell and various recommendations made in the future can be applied to similar postures in the entire plant. The results of the analyses show that 14 different work postures in Cell A, Cell P1, Cell P2, Cell P3, Cell P4, and Cell P5 need to be modified. Out of all these analyzed postures, only one of the work postures is in critical need of immediate attention.

The model in Fig. 5.1 was presented to show the detailed processes that could be followed in achieving results using the RULA analysis. Names such as Fred 15.2 were assigned to the postures where the names are arbitrary names and the numbers stand for the time displayed in the digital motion capture. Table 5.1 shows the various input options selected for each work posture. These options are dependent on the condition associated with these postures being analyzed. From Table 5.2, we selected the repeat frequency based on the number of times the posture occurs in a minute. We also specified the load on the posture and the body part on which the load is acting. The scores obtained ranges from 1 to 7 and can vary based on the body part being considered. The various body part range for RULA score is presented in B3.

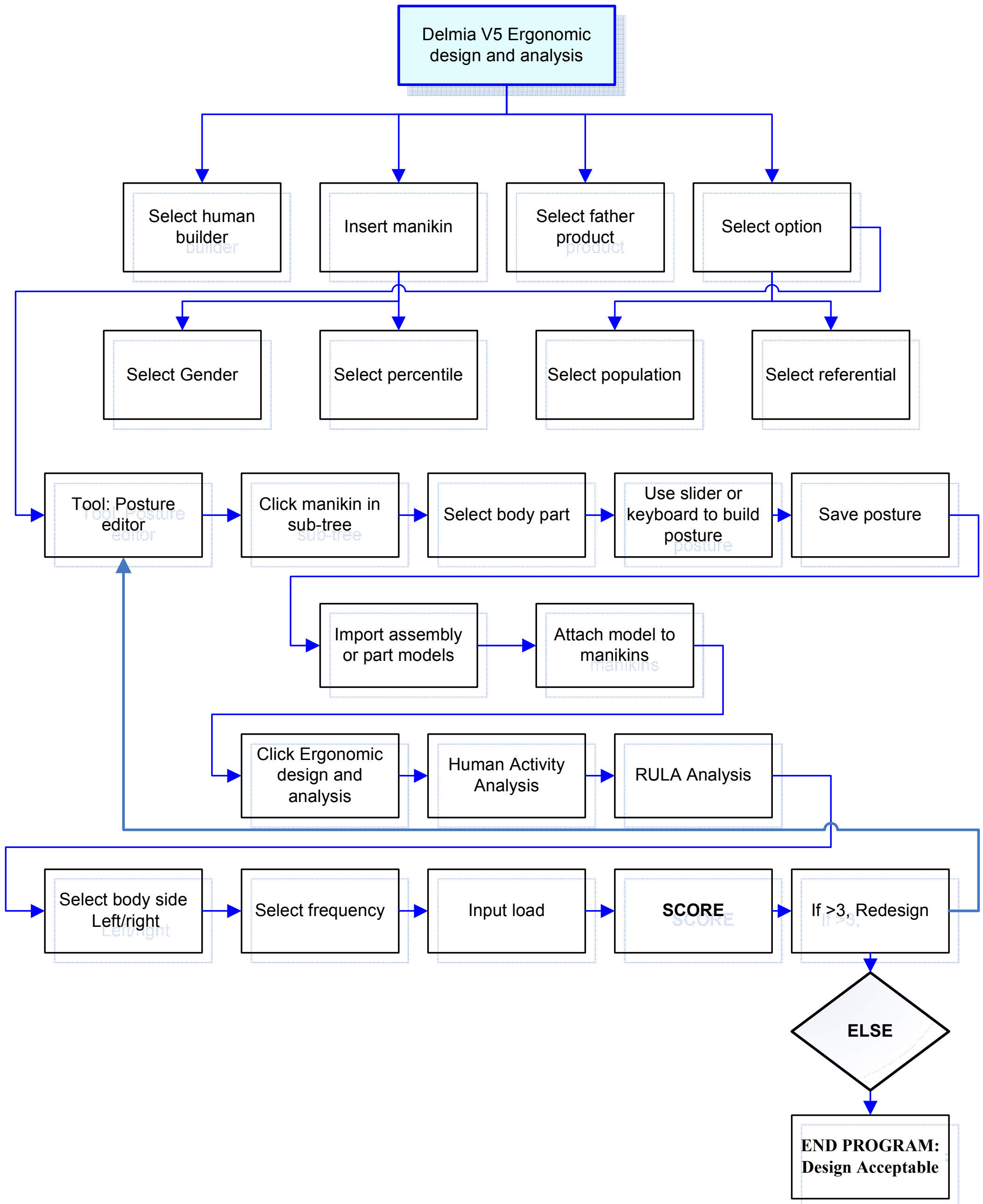

FIG 5.1 MODEL FOR RULA ANALYSES

Table 5.1: RULA Analyses Input And Results

Name	Posture	Repeat Freq.	Arm supported /person leaning	Arms working across midline	Load (kg)	Score	Description
Fred 0.04	Intermittent	<4Times/min	_	_	0	2	Acceptable
Fred 3.22	Static	>4Times/min	yes		1	5	Investigate further and change soon
Fred 3.28	Repeated	>4Times/min	yes	_	3	6	Investigate further and change soon
Fred 3.37	Static	<4Times/min	_	yes	3	6	Investigate further and change soon
Fred 4.04	Static	<4Times/min	yes	yes	3	6	Investigate further and change soon
Fred 4.55	Intermittent	<4Times/min	yes	yes	3	5	Investigate further and change soon
Fred 12	Intermittent	<4Times/min	yes	_	4	5	Investigate further and change soon
Jane13.42	Repeated	>4Times/min	yes	_	3	6	Investigate further and change soon
Jane15.14	Intermittent	<4Times/min	yes	_	3	4	Investigate further
Jane16.12	Intermittent	<4Times/min	_	_	3	5	Investigate further and change soon
Jane18.47	Intermittent	<4Times/min	yes	_	3	3	Investigate further
Jane19.23	Static	<4Times/min	_	_	3	7	**Investigate further and change immediately**
Jane20.00	Intermittent	<4Times/min	yes	_	2	6	Investigate further and change soon
Jane22.06	Static	<4Times/min	yes	_	3	5	Investigate further and change soon
Jane23.58	Intermittent	<4Times/min	yes	_	20	6	Investigate further and change soon

NOTE:

- The names e.g. Fred 04. 04 or Jane 15.14 represents specific times in the video at which the posture occurred.
- Intermittent/Static Posture: A posture that occurs less than 4 times in a minute
- Repeated Posture: A posture that occurs greater than 4 times in a minute
- Load: The load attached to the manikins left or right side
- Description: This is based on the score and presents a result of the analyses

5.3.1 Injury levels on body parts

Tables 5.2, 5.3, and 5.4 presents the various scores and associated colors obtain from the RULA analysis conducted on various postures on the assembly line in Chapter 3.

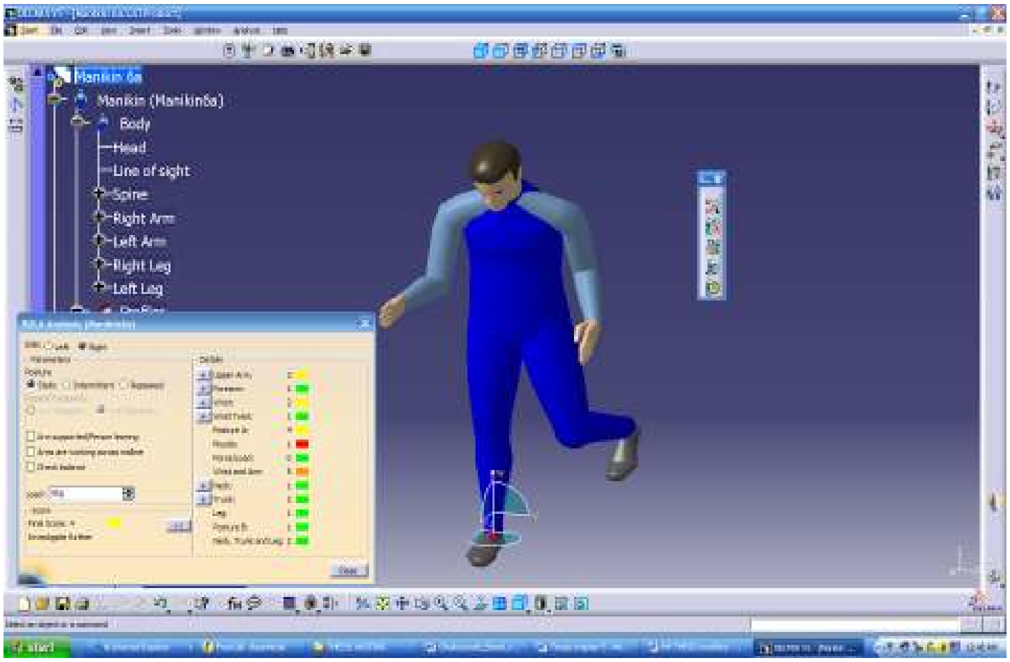

FIG. 5.2 SCREEN CAPTURE ON RULA ANALYSIS

TABLE 5.2: RULA RESULTS 1

Body Part	Fred 0.04		Fred 3.22		Fred 3.28		Fred 3.37		Fred 4.04	
Upper Arm	2		2		2		2		3	
Fore Arm	1		2		2		2		2	
Wrist	1		1		1		1		1	
Wrist Twist	1		1		1		1		1	
Posture A	2		3		3		3		3	
Muscle	0		1		1		1		1	
Force/Load	0		0		2		2		2	
Wrist and Arm	2		4		6		6		6	
Neck	2		3		1		2		4	
Trunk	2		4		3		2		2	
Leg	1		1		1		1		1	
Posture B	2		4		2		2		2	
Neck, Trunk, & Leg	2		5		5		5		5	
Final Score	**2**		**5**		**6**		**6**		**6**	
Description	**Acceptable**		**Investigate and change immediately**		**Investigate and change immediately**		**Investigate and change immediately**		**Investigate and change immediately**	

NOTE:

RED	change immediately	7
ORANGE	change soon	5, 6
YELLOW	investigate further:	3, 4
GREEN	Acceptable	1, 2

TABLE 5.3: RULA RESULTS 2

Body Part	Fred 4.55		Fred 12		Jane 13.42		Jane 15.14		Jane 16.12	
Upper Arm	1		2		1		2		1	
Fore Arm	3		2		2		2		2	
Wrist	1		1		1		1		1	
Wrist Twist	1		1		1		1		1	
Posture A	2		3		2		3		2	
Muscle	0		0		1		0		0	
Force/Load	1		1		2		1		1	
Wrist and Arm	3		4		5		4		3	
Neck	6		3		3		2		6	
Trunk	5		4		2		3		5	
Leg	1		1		1		1		1	
Posture B	1		4		2		3		1	
Neck, Trunk, & Leg	1		5		5		4		1	
Final Score	**5**		**5**		**6**		**4**		**5**	
Description	**Investigate further and change soon**		**Investigate further and change soon**		**Investigate further and change soon**		**Investigate further**		**Investigate further and change soon**	

TABLE 5.4: RULA RESULTS 3

Body Part	Jane 18.47		Jane 19.23		Jane 20.00		Jane 22.06		Jane 23.58	
Upper Arm	2		2		2		2		3	
Fore Arm	2		1		2		1		2	
Wrist	1		1		1		1		1	
Wrist Twist	1		1		1		1		2	
Posture A	3		2		3		2		4	
Muscle	0		1		0		1		0	
Force/Load	1		2		1		2		2	
Wrist and Arm	4		5		4		5		6	
Neck	1		1		5		1		1	
Trunk	3		4		5		1		3	
Leg	1		1		1		1		1	
Posture B	2		3		6		1		2	
Neck, Trunk, & Leg	3		6		7		4		4	
Final Score	**3**		**7**		**6**		**5**		**6**	
Description	**Investigate further**		**Investigate and change immediately**		**Investigate further and change soon**		**Investigate further and change soon**		**Investigate further and change soon**	

5.3.2 EVALUATION OF RULA ANALYSIS RESULTS

The study shows that one of the human postures studied is in a critical condition, 11 of the postures needs to be investigated and changed soon, 2 postures need to be investigated further, and 1 work posture is acceptable. For each work posture studied, we decided to study further the affected body parts. Tables 5.2, 5.3, and 5.4 presents the various body part analysis. Fred 3.22, Jane 19.23, Jane 22.06, and Jane

13.42 are experiencing critical muscle conditions as can be seen from the associated colors in Tables 5.2, 5.3, and 5.4. The critical conditions observed in the multiple body parts were seen in Jane 20.00, Fred 3.22, Fred 3.28, Fred 3.37, Fred 4.04, Fred 12, and Jane 13.42. Critical problems associated with arms are observed in Fred 3.38, Fred 3.37, Fred 4.04, Jane 19.23, Jane 22.06, Jane 23.25, and Jane 13.42. For the neck, critical conditions exist in Jane 20.00 and Fred 4.55.

TABLE 5.5: POSTURES ANALYZED AND THE RELATED SCORES

SCORE	No of postures with associated score	Description of score
7	1 posture	Investigate and change immediately
6	6 postures	Investigate and change soon
5	5 postures	Investigate and change soon
4	1 posture	Investigate further
3	1 posture	Investigate further
2	1 posture	Acceptable.

Other conditions of urgent concern can be observed from Tables 5.2, 5.3, and 5.4. The final score were used to present a total score of the different body parts in the analysis. Table 5.5 presents the number of postures studied as

5.4 CASE STUDY: LIFT ANALYSES

The NIOSH guideline was applied in the Delmia V5© for the lift analysis conducted on the assembly line of Chapter 3. One posture in the entire line was studied as most of the lift operations in the lines are already automated. For the purpose of simplicity, we developed the model in Fig. 5.3 to act as a guideline for the previously complex process. The NIOSH equations used in the Delmia V5© environment are shown in equations 5.1 and 5.2.

$$RWL = LC \times HM \times VM \times DM \times AM \times FM \times CM \qquad (5.1)$$

$$LI = \frac{Load\ Weight}{\mathrm{Re}commended\ \ Weight\ Limit} = \frac{L}{RWL} \tag{5.2}$$

The various variables associated with equations 5.1 and 5.2 are described in Table 2.1a and Table 2.1.

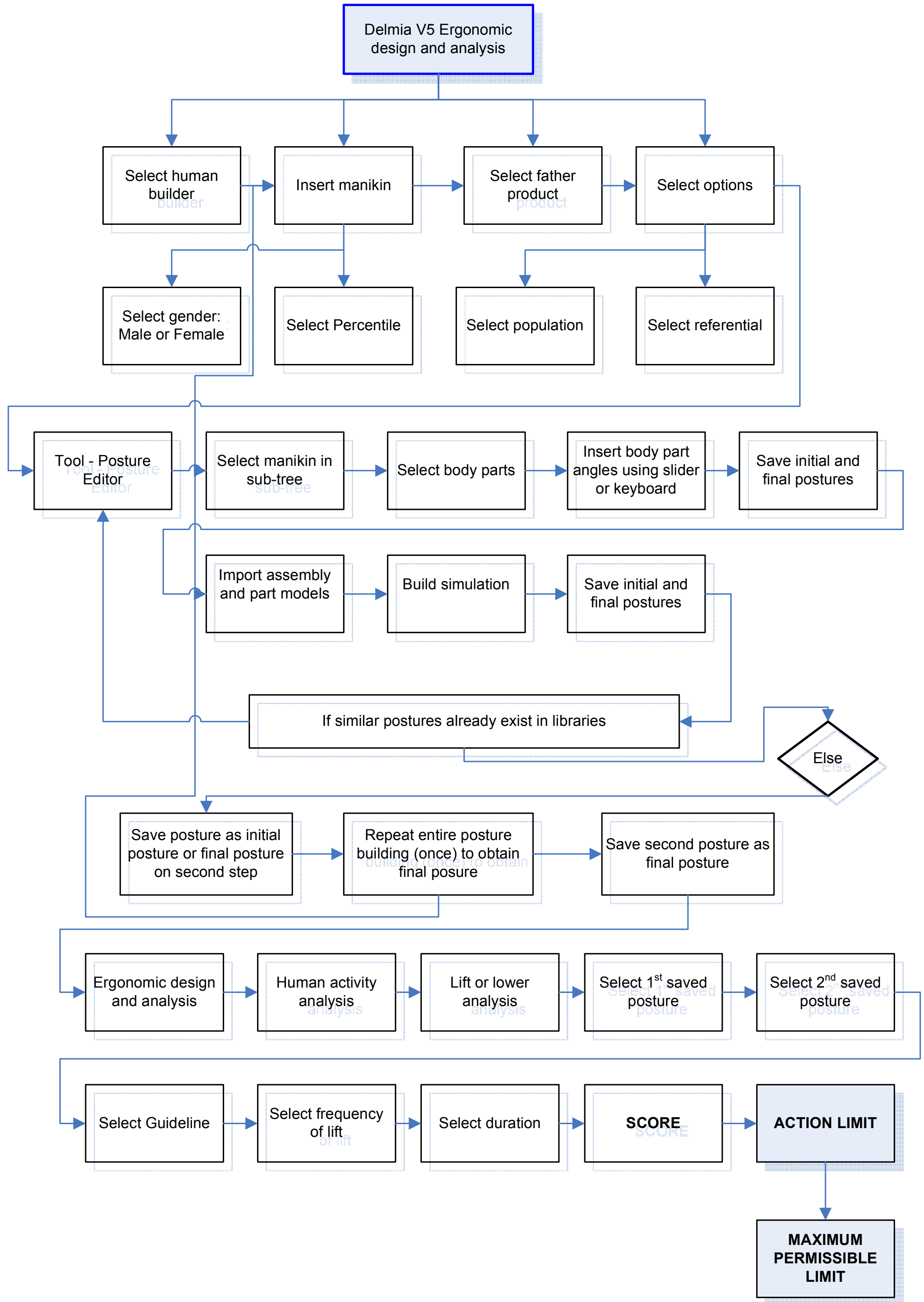

FIG 5.3: MODEL FOR LIFT LOWER POSTURAL ANALYSES

Table 5.6 presents the various input variables and their values as used in this analysis while Table 5.7 presents the results of the analysis.

TABLE 5.6: LIFT LOWER ANALYSES INPUT

Guideline: NIOSH 1991 (Fred 1.56 mins) (Primary Assembly Line)	
Mass of component	11.67kg
1 lift every	180secs
Duration of Lift	1hr or less
Coupling condition	Good

TABLE 5.7: LIFT LOWER ANALYSES RESULTS

Origin: Recommended weight limit (RWL):	9.54kg
Lifting Index (LI)	1.26
Warning: Poor foot to foot coupling in final posture	

5.4.1 EVALUATION OF LIFT LOWER RESULTS

We observed that the recommended weight limit of the lift operation analyzed is 9.54 kg while the actual component weight is 11.67 kg as can be seen in Table 5.6 and Table 5.7. This leaves us with a lifting index (LI) of 1.26. Since LI>1, the operation is unsafe for humans under that particular posture. Table 4.1 provides various steps that can be used to improve the various lifting operations. For the particular lift operation studied, the results of the analysis show it is unsafe for humans and needs to be changed to avoid further risk of injuries.

We used the Snook and Ciriello guideline in the Delmia V5© to perform the push-pull analysis. The following parameters were used as input variables: (1) distance of push, (2) distance of pull, (3) frequency of push, and (4) population sample. The output parameters of the push-push analysis are: (1) the maximum acceptable initial force, and (2) the maximum acceptable sustained force. Table 5.8 presents the values of the various input parameters and the results obtained from the analysis. Following the insight gain from various procedures both in Chapters 3 and 4, we were able to develop the model in Fig. 5.4 to act a guide for the push-pull analysis using the biomechanical model approach

TABLE 5.8: PUSH PULL ANALYSES INPUT PARAMETERS

GUIDELINE: SNOOK AND CIRIELLO 1991	
1 PUSH EVERY	3600 SECS
DISTANCE OF PUSH	310 IN.
DISTANCE OF PULL	20 IN.
MAXIMUM ACCEPTABLE INITIAL FORCE: PUSH/PULL	• PUSH: 239.73N • PULL: N/A
MAXIMUM ACCEPTABLE SUSTAINED FORCE: PUSH/PULL	• PUSH: 133.14N • PULL: N/A

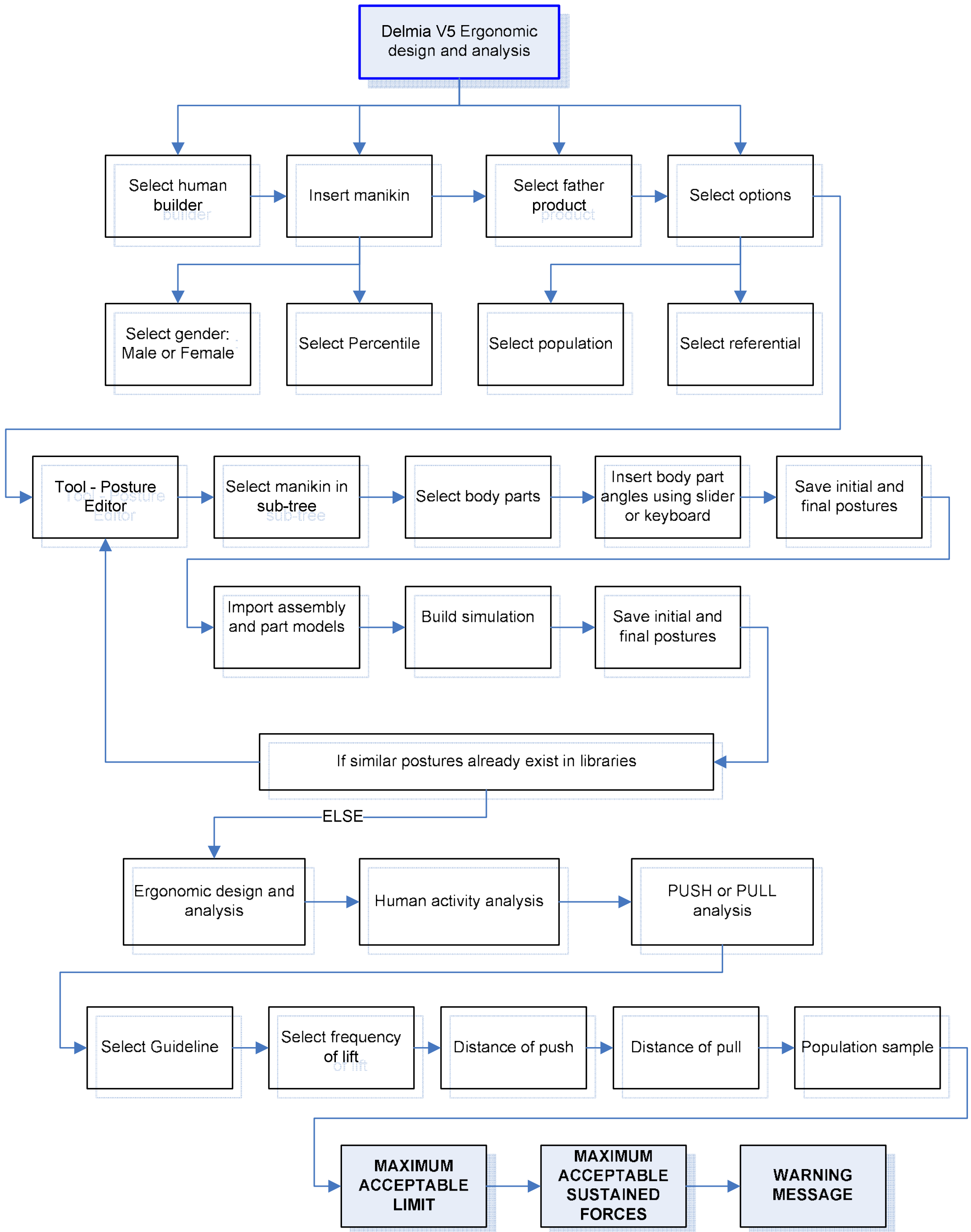

FIG 5.4: PUSH-PULL ANALYSES MODEL

5.5.1 EVALUATION OF THE PUSH-PULL ANALYSIS RESULT

From the push-push analysis result presented in Table 5.8, the maximum acceptable initial force and maximum acceptable sustained forces were obtained for the single push operation studied. The values obtained were 239.73N and 133.136N for the maximum acceptable initial force and maximum acceptable sustained forces respectively. With these standards in mind, one is supposed to measure the initial and sustained forces and compare them with the results obtained. However, measuring the initial and sustained forces needs special equipments such as the load cell and the spring scale. Using these standards, the various pull and push operations should be measured with load cells or spring scales to ensure the maximum initial or sustained forces do not exceed that obtained from push-pull analysis. In a much simpler approach, we can analyze these forces by converting them to mass using the upper limit force which in this case is 239.73N. Hence, we are not expected to push more than 23kg of mass on the floor or keep a 13kg mass in motion over the specified period of time. By further evaluating the cart and the friction on the wheels, this weight of 23kg for initial force and 13kg for sustained force will reduce. From simple evaluation while putting into consideration factors such as friction on wheels of the trolley, one could identify the push operation in the example system in Chapter 3 as safe.

5.6 CASE STUDY: CARRY ANALYSES

The input and output variables used in the carry analysis are presented in Table 5.9. There is only one output parameter for the analyses which is the maximum acceptable weight. In Fig. 5.5, we present a simplified model for carry analysis using the Delmia V5© software.

TABLE 5.9: CARRY ANALYSES INPUT AND RESULTS

GUIDELINE: SNOOK AND CIRIELLO 1991	
FREQUENCY	1 CARRY EVERY 180SECS
DISTANCE OF CARRY	84IN
POPULATION SAMPLE	50%
MAXIMUM ACCEPTABLE WEIGHT	**186 – 232N**

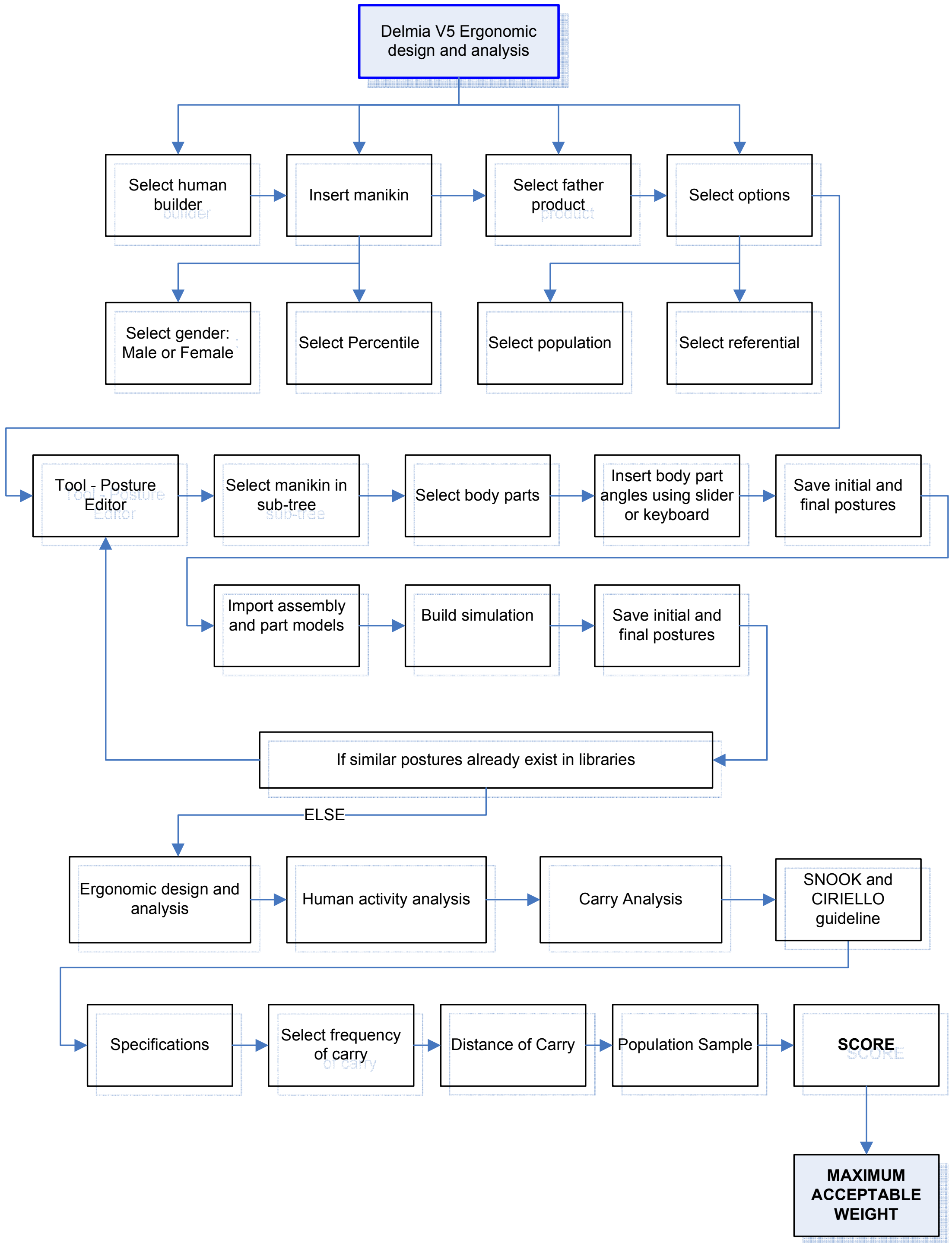

FIG. 5.5: MODEL FOR CARRY ANALYSES

5.6.1 Evaluation Of The Carry Analysis Result

The results presented in Table 5.9 show that the maximum acceptable weight of carry for the example posture considered is between 186 N and 232 N. The set standard for the maximum weight of carry in the assembly line in Chapter 3 is 50lb. Hence, the current carry operation analyzed fall within safe limits.

5.7 Case study: Results From Biomechanical Single Action Analyses

This biomechanics single action analysis option in Delmia V5© was used to generate information such as the L4-L5 moment, L4-L5 compression, body load compression, axial twist compression, flex./ext. compression, and L4/L5 joint shears. Other results obtained from this analysis are presented in A1 and these results include abdominal forces acting on the manikin, abdominal pressures, manikins ground reactions, spine limits, joint moment strength data, reaction forces, and manikins body segment positions in the work space. For each work posture analyzed using the RULA analysis option, the biomechanics single action analysis was also conducted. Information about the manikin segments such as the angle along the XY and YZ plane, proximal and distal coordinates of each individual segment, and the length of the segments were also obtained. Fig. 5.6 presents various steps and input parameters used to obtain the results of the biomechanics single action analysis.

TABLE 5.10 SUMMARIES OF BIOMECHANICS SINGLE ACTION ANALYSES

Analyses	**L4-L5 Moment (N_m)**	**L4-L5 Compression (N)**	**Body Load Compression (N)**	**L4-L5 Joint Shear (N)**
Fred 0.04	12	775	439	21 Posterior
Fred 3.22	22	1863	390	2 Posterior
Fred 3.28	11	1204	427	5 Posterior
Fred 3.37	32	1425	424	54 Anterior
Fred 4.04	60	1505	402	87 Anterior
Fred 4.55	79	2379	278	189 Anterior
Fred 12.00	33	1685	401	37 Anterior
Jane 13.42	26	927	369	35 Anterior
Jane 15.14	78	1563	259	159 Anterior
Jane 16.12	76	1738	247	173 Anterior
Jane 18.47	65	1364	263	126 Anterior
Jane 19.23	62	1384	323	103 Anterior
Jane 20.00	55	1662	289	140 Anterior
Jane 22.06	3	485	376	26 Posterior
Jane 23.58	91	1778	259	140 Anterior

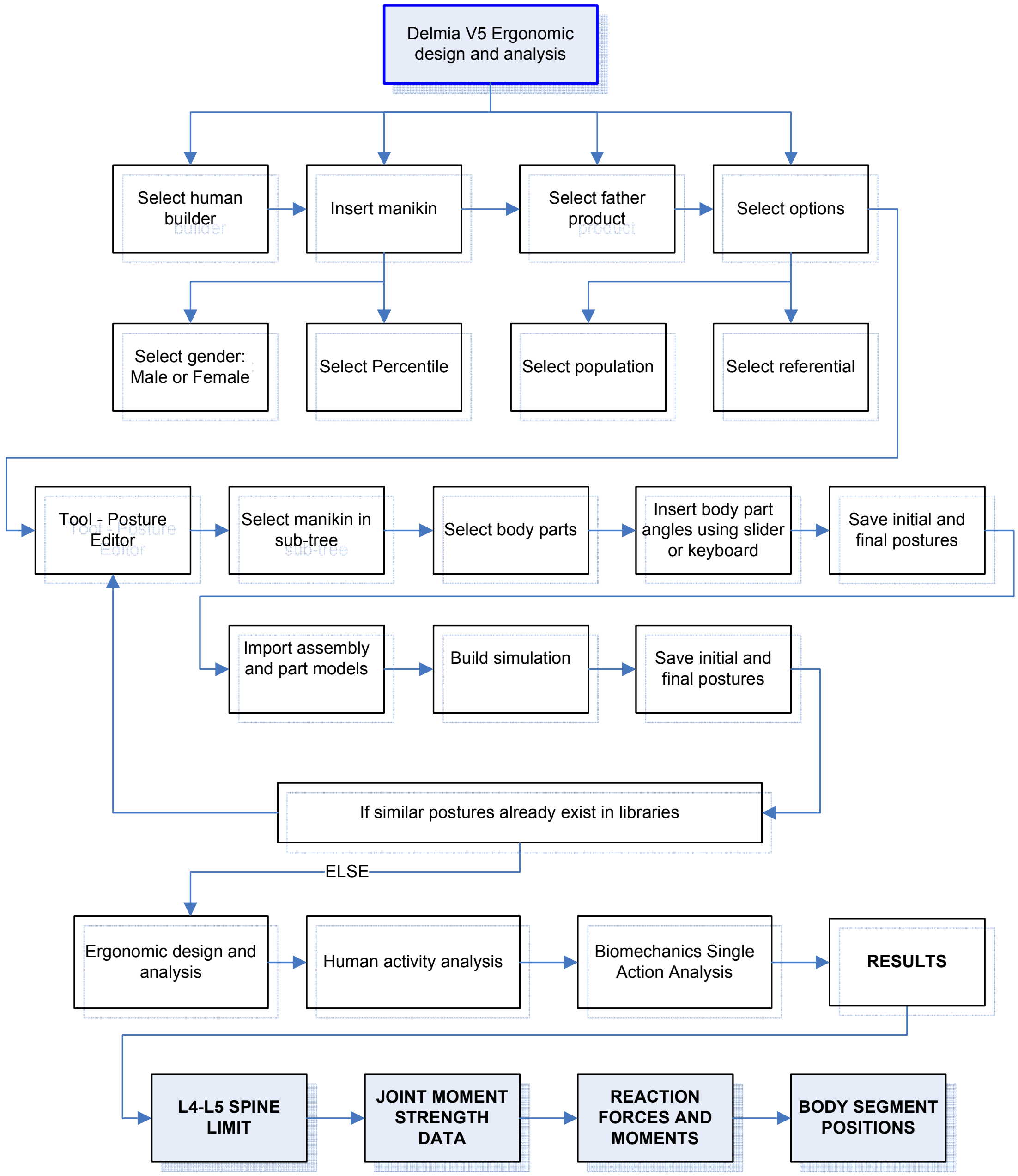

FIG. 5.6: MODEL FOR BIOMECHANICS SINGLE ACTION ANALYSES

5.7.1 EVALUATION OF THE BIOMECHANICS SINGLE ACTION ANALYSIS RESULT

The L4/L5 moment presents the moment created along the L4/L5 disc due to the mass of the body and the load acting on the hands. In order for a subject to maintain stability, he is expected to consistently resist the load moment created by these forces by consciously actuating his/her trunk muscles (Ergowatch, 2001). This resistive moment needed to actually keep the body in equilibrium is known as the L4/L5 moment. The extensor moment of the L4-L5 moment is expressed as positive and a flexor moment expressed as negative. In the results presented above in Table 5.10 and using Fred 4.55, Fred 12.00, and Jane 13.42 as examples, it could be found that Fred 4.55 experiences a greater resistive moment to maintain stability than Fred 12.00 and Jane 13.42 (Emodi et al., 2007). This results to a greater weight on the trunk and can also be identified through the red color associated with the trunk of Fred 4.55 in Table 5.10.

The L4-L5 compression value which represents the compressive force acting on the L4-L5 inter-vertebral joint is also affected by this condition. This compressive force is as a result of forces due to the mass of the body and the forces acting on the hand and trunk muscles/ligaments that are used to generate the support moment. The score experienced by Fred 4.55 due to the force of compression is greater than that of Fred 12.00 and the compressive force experienced by Fred 12.00 is greater than that of Jane 13.42. These differences can also be seen in the associated colors of the trunk which is the primary location of the L4-L5 disc as shown in Table 5.10. Also in Table 5.10, Fred 4.55 is associated with a color of red and a score of 5 while Fred 12.00 is associated with a lower L4/L5 compressive force which indicates a score of 4 and a yellow color. Jane 13.42 which had the least compressive force indicates a score of 2 and a color of green (Emodi et al., 2007).

The body load compression is represented by the load-force category. Fred 12.00 has the greatest body load compression and the effect of this can be observed on the neck, trunk and leg body classes. From Table 5.10 the score associated with the body load compression for Fred 12.00 is ‘4’ and with a color of yellow showing the condition should be considered for modification.

L4-L5 Reaction Shear is the resultant shear force due to the mass of the upper body and the forces created on the hands on the L4/L5 joint. Shear refers to the force that acts parallel or tangent to a surface to create a sliding motion between two objects. The effect of this is noticed mainly on the muscles with Jane 13.42 experiencing the greatest impact. The L4-L5 shear has a similar effect as the flex.-ext. compression which also affects the muscles and can be verified by comparing the results of Table 2 with that of Table 3.

The L4-L5 Joint Shear is the resultant shear force due to the sum of the reaction shear and the muscle/ligament shear. This value includes the effects of ligament muscles forces and the actual shear experienced at the L4-L5 joint. This also has a similar effect as the L4-L5 reaction shear judging from the values obtained from the analysis.

All these results provide more detailed information on the exact torques, forces, and stresses acting on the human body. However, none of these results present as an entity the level of risk associated with a work activity as injuries are caused by a combination of these factors. The comprehensive biomechanical single action analysis results are presented in A1.

5.8 CASE STUDY: INJURY COST

Table 5.11 was generated to link the SWCB injury classification with the Delmia V5© injury classification. This was then used to obtain the actual repetitive injury cost from the SWCB injury cost database.

In Table 5.11, we present the association between the Delmia V5© and the SWCB injury information. The method of statistical analysis was then used to associate injury costs with various injury levels. This was carried out using a statistical method called the percentile. This method breaks down the injury costs into different groups of unequal intervals.

TABLE 5.11: DELMIA AND SWCB CLASSIFICATION

DELMIA V5©	**SWCB**			
	PART OF BODY	DIAGNOSIS	PART OF BODY GROUP	PART OF BODY SUB-GROUP
UPPER ARM	UPPER ARM	Sprains/Strains Soreness, Pain, Hurt		Arms
FOREARM	FORE ARM	Sprains/Strains Soreness, Pain, Hurt		Arms
WRIST		Sprains/Strains Soreness, Pain, Hurt		Wrist
MUSCLE		Traumatic Injuries to Muscles/Tendons/Ligaments/ And Joints		
WRIST/ ARM	HANDS AND WRIST	Sprains/Strains Soreness, Pain, Hurt		Multiple Upper Extremity Locations
NECK		Sprains/Strains Soreness, Pain, Hurt		Neck: Except Internal Location Of Diseases Or Disorders
TRUNK		Sprains/Strains Soreness, Pain, Hurt	Trunk	
LEG		Sprains/Strains Soreness, Pain, Hurt		Legs
NECK, TRUNK LEG		Sprains/Strains Soreness, Pain, Hurt		Neck Trunk Legs

5.8.1 PERCENTILE CLASSIFICATION

The basic algorithm used to obtain the percentile classification is shown in Equation 5.3.

$$\frac{cf_i + .5(f_i)}{N} \times 100\% \qquad (5.3)$$

Where cf_i is the cumulative frequency for all scores less than the score of interest, f_i is the frequency of the score of interest, and N is the sample size. However, this is not an equal interval scale and was used because most statistical information involving human anthropometry uses percentiles for most classifications. Information collected from SWCB includes injury information from 2001 to 2005. During the analysis, we made several underlying assumptions and as stated below:

ASSUMPTIONS:

- All the other injury classes in Delmia which are not directly represented in SWCB injury classification are indirectly represented in other parts of the SWCB classification. Example: force/load is not represented in SWCB, however, the effect of these are represented indirectly in the muscles, trunk, wrist and arm, etc.
- Injury levels can be classified into un-equal intervals using the percentile range.

Table 5.12 presents the percentile breakdown based on a maximum achievable percentile range of 90th percentile. Hence, the score of 90 was shared into equal intervals for each of the body groups being analyzed and the number of percentile groups depends on the body group being studied as individual body groups have varying ranges. Also, Table 5.13 presents the injury level costs associated with each of the percentile classes in Table 5.12 based on the data generated from SWCB.

TABLE 5.12: PERCENTILE BREAKDOWN BASED ON MAXIMUM PERCENTILE OF 90%

Segment	**Range**	**Percentile range (%)**						
		1	**2**	**3**	**4**	**5**	**6**	**7**
UPPER ARM	**1-6**	0	18	36	54	72	90	
FOREARM	**1-3**	0	45	90				
WRIST	**1-4**	0	30	60	90			
MUSCLE	**1-2**	0	90					
WRIST/ ARM	**1-7**	0	15	30	45	60	75	90
NECK	**1-6**	0	18	36	54	72	90	
TRUNK	**1-6**	0	18	36	54	72	90	
LEG	**1-7**	0	15	30	45	60	75	90
NECK, TRUNK LEG	**1-7**	0	15	30	45	60	75	90

TABLE 5.13: PERCENTILE COST CLASSIFICATION

Segment	Range	Costs through percentile ranges in Canadian dollars (× $1000)						
		1	2	3	4	5	6	7
UPPER ARM	**1-6**	0	0.35	0.98	4.32	30.11	1082.43	
FOREARM	**1-3**	0	0.98	20.34				
WRIST	**1-4**	0	0.61	4.10	312.52			
MUSCLE	**1-2**	0	74.92					
WRIST/ ARM	**1-7**	0	0.15	0.57	1.62	3.07	10.423	86.51
NECK	**1-6**	0	0.35	0.94	2.25	7.95	154.98	
TRUNK	**1-6**	0	0.37	1.51	5.86	34.31	429.70	
LEG	**1-7**	0	0.18	0.59	1.41	3.73	19.67	359.73
NECK, TRUNK LEG	**1-7**	0	0.33	0.79	1.90	5.09	24.02	271.75

5.8.2 COST EFFECTS ON DIFFERENT BODY PARTS

The amount in Canadian dollars associated with each level of injury was obtained from this study by associating the cost classifications in Table 5.13 with the injury levels presented in Tables 5.3, 5.3, and 5.4. The cost implication of these results in Table 5.3, 5.3, and 5.4 are presented in Tables 5.14, 5.15, and 5.16. Table 5.17 presents a summary result of the cost analysis.

TABLE 5.14: RULA ANALYSES SCORES AND COST 90TH PERCENTILE (× $1000)

Body Part	**Fred 0.04**		**Fred 3.22**		**Fred 3.28**		**Fred 3.37**		**Fred 4.04**	
	C	**COST**	**C**	**COST**	**C**	**COST**	**C**	**COST**	**C**	**COST**
Upper Arm	2	0.35	2	0.35	2	0.35	2	0.35	3	0.98
Fore Arm	1	0.00	2	0.98	2	0.98	2	0.98	2	0.98
Wrist	1	0.00	1	0.00	1	0.00	1	0.00	1	0.00
Muscle	1	0.00	2	74.92	2	74.92	2	74.92	2	74.92
Wrist and Arm	2	0.15	4	1.62	6	10.43	6	10.43	6	10.43
Neck	2	0.35	3	0.94	1	0.00	2	0.35	4	2.25
Trunk	2	0.37	4	5.86	3	1.51	2	0.37	2	0.37
Leg	1	0.00	1	0.00	1	0.00	1	0.00	1	0.00
Neck, Trunk, & Leg	2	0.33	5	5.09	5	5.09	5	5.09	5	5.09
TOTAL COST		**1.55**		**89.76**		**93.28**		**92.50**		**95.02**

TABLE 5.15: RULA ANALYSES SCORES AND COST 90TH PERCENTILE (× $1000)

Body Part	**Fred 4.55**		**Fred 12**		**Jane 13.42**		**Jane 15.14**		**Jane 16.12**	
	C	**COST**	**C**	**COST**	**C**	**COST**	**C**	**COST**	**C**	**COST**
Upper Arm	1	0.00	2	0.35	1	0.00	2	0.35	1	0.00
Fore Arm	3	20.34	2	0.98	2	0.98	2	0.98	2	0.98
Wrist	1	0.00	1	0.00	1	0.00	1	0.00	1	0.00
Muscle	1	0.00	1	0.00	2	74.92	1	0.00	1	0.00
Wrist and Arm	3	0.57	4	1.62	5	1.62	4	1.62	3	0.57
Neck	6	154.98	3	0.94	3	0.94	2	0.35	6	154.98
Trunk	5	34.31	4	5.86	2	0.37	3	1.51	5	34.31
Leg	1	0.00	1	0.00	1	0.00	1	0.00	1	0.00
Neck, Trunk, & Leg	0	0.00	5	5.09	5	5.09	4	1.90	0	0.00
TOTAL COST		**210.18**		**14.84**		**83.92**		**6.70**		**190.83**

TABLE 5.16: RULA ANALYSES SCORES AND COST 90TH PERCENTILE **(× $1000)**

Body Part	**Jane 18.47**		**Jane 19.23**		**Jane 20.00**		**Jane 22.06**		**Jane 23.58**	
	C	**COST**	**C**	**COST**	**C**	**COST**	**C**	**COST**	**C**	**COST**
Upper Arm	2	0.35	2	0.35	2	0.35	2	0.35	3	0.98
Fore Arm	2	0.98	1	0.00	2	0.98	1	0.00	2	0.98
Wrist	1	0.00	1	0.00	1	0.00	1	0.00	1	0.00
Muscle	1	0.00	2	74.92	1	0.00	2	74.92	1	0.00
Wrist and Arm	4	1.62	5	1.62	4	1.62	5	1.62	6	10.43
Neck	1	0.00	1	0.00	5	7.95	1	0.00	1	0.00
Trunk	3	1.51	4	5.86	5	34.31	1	0.00	3	1.51
Leg	1	0.00	1	0.00	1	0.00	1	0.00	1	0.00
Neck, Trunk, & Leg	3	0.79	6	24.02	7	271.75	4	1.90	4	1.90
TOTAL COST		**5.24**		**106.78**		**316.95**		**78.79**		**15.79**

WHERE C STANDS FOR CLASS

Table 5.17 Cost summaries for 90TH Percentile

MANIKIN	DESCRIPTION	COST (× $1000)
Fred 0.04	Acceptable	1.548
Fred 3.22	Investigate and change immediately	89.76
Fred 3.28	Investigate and change immediately	93.28
Fred 3.37	Investigate and change immediately	92.50
Fred 4.04	Investigate and change immediately	95.02
Fred 4.55	Investigate and change immediately	210.18
Fred 12.0	Investigate and change immediately	14.84
Jane 13.42	Investigate and change immediately	83.92
Jane 15.14	Investigate further	6.70
Jane 16.12	Investigate and change immediately	190.83
Jane 18.47	Investigate further	5.24
Jane 19.23	Investigate and change immediately	106.78
Jane 20.0	Investigate further and change soon	316.95
Jane 22.06	Investigate further and change soon	78.79
Jane 23.58	Investigate further and change soon	15.79
Total actual cost	$ 1,402,142.56 × **0.02** ≈ $28,000.00	

Where **0.02** is used as the index factor for the assembly line in Chapter 3

The obtained costs vary based on the injury record of an assembly line. This led to the generation of a multiplicative index. The multiplication index is multiplied with the total cost to obtain the actual expected cost for a particular plant of interest. For instance, most safe plants do not experience such costs as obtained through the analysis. Hence, we generated a range of 0 to 1. For instance, for a very safe plant that experiences a low injury cost, the multiplicative index of 0.05 may be multiplied with the total cost. A more acceptable way of generating this index is by comparing the current costs associated with a specific cell in the plant with the cost obtained using SWCB database. The cost of SWCB analysis is then divided by the actual cost of injuries obtained over the years in the same cell to obtain the multiplicative index.

This index can then be used as the basis for all other similar cells in the plant. This condition is possibly only when the line being considered or a similar line has been in production for a while. In the case of this assembly line in Chapter 3, the total cost would be $1,402,142.56×0.02 ≈ $28,000.00. This line was given a multiplicative index of 0.02 based on previous injury record. This is an excellent performance with regards to safety. A more problematic line might have a multiplicative index as high as 0.9. A multiplicative index value that is greater than 1 denotes a critical situation that needs to be addressed through an immediate shut down of the line.

Fig. 5.7 presents the injury cost associated with various body parts based on the analysis conducted. From the presentation below, it could be seen that injuries associated with the muscles are of most urgent concern. These are followed by injuries associated with the neck, trunk, leg, wrist, and arm.

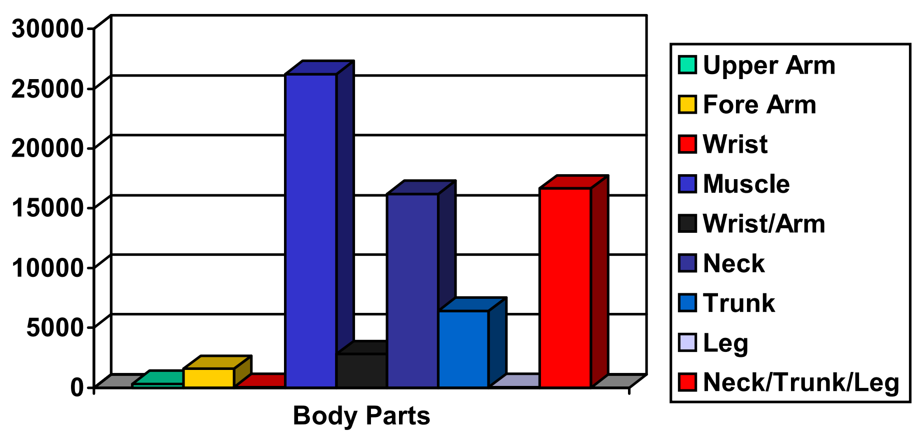

FIG. 5.7: BODY PART ANALYSIS

5.8.3 COST ANALYSIS IN VARIOUS CELLS

Injury costs in individual cells were also studied. Fig. 5.8, 5.9, 5.10, 5.11, and 5.12 presents the various injury costs for different cells.

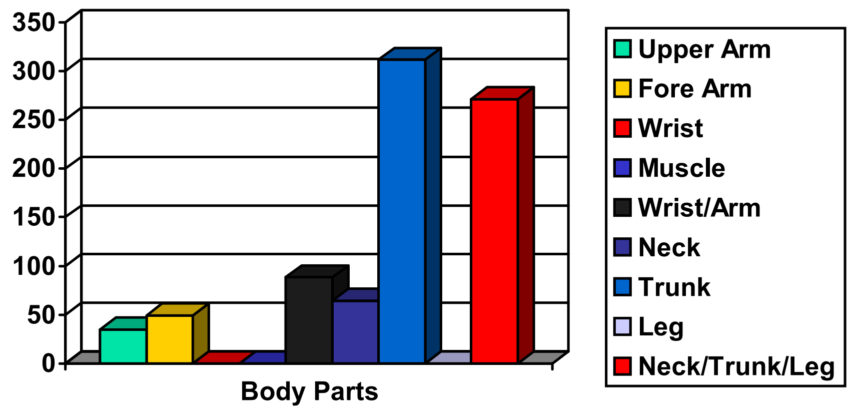

FIG. 5.8: CELL A

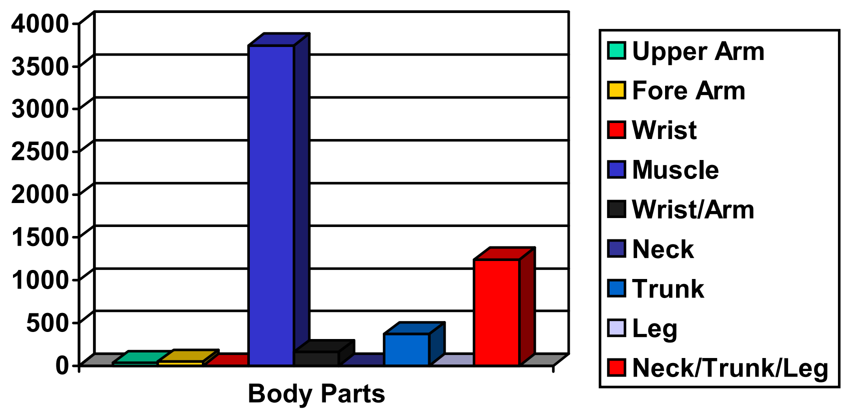

FIG. 5.9: CELL P1

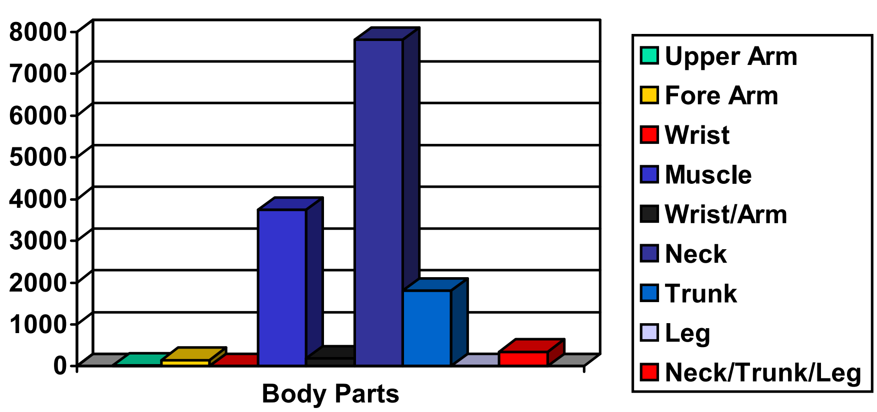

FIG. 5.10: CELL P3

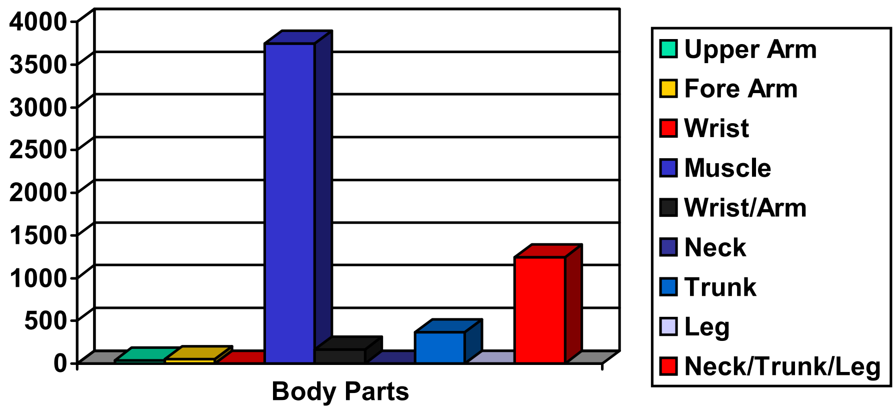

FIG. 5.11: CELL P4

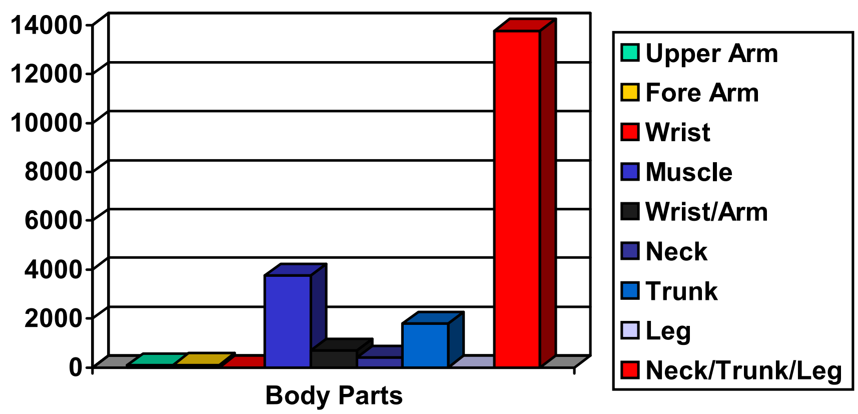

FIG. 5.12: CELL P5

5.8.4 EVALUATION OF INJURY COST IN CELLS A, P1, P2, P3, P4, AND P5

We have observed that Cell P1 has the greatest potential for increased injury cost. This trend is followed by Cell P5 and Cell P3. The safest assembly line observed during this analysis is Cell P2.

Further evaluation of Cell A, shows that the trunk has the highest injury risk potential. This trend is followed by the multiple body parts represented by neck/trunk/leg. Other significant injuries on the Cell A could be observed in the wrist/arm, and the neck. Cell P1 also shows a trend with the muscles experiencing the greatest injury cost. This is followed by the multiple body parts on the neck/trunk/leg. Cell P3 is unique as there is an urgent concern associated with the neck. Other concerns are associated with the muscle, trunk, and neck/trunk/leg. These can be observed in Fig. 5.10. The results of Cell P4 also show a great concern for the muscles. However, other major concerns include the neck/trunk/leg, and the trunk. From the analysis conducted on Cell P5, it is observed that the neck/trunk/leg is at risk. This assembly cell also has the muscle and the trunk as body parts at risk. Section 5.9 discusses the results of the synthesis.

5.9 RESULTS ON SYNTHESIS

In Chapter 4, we mentioned the need to implement a design change on a particular posture in the assembly system in Chapter 3. We were able to implement a re-design using Process 1 in the rule of thumb table presented in Table 4.1. The results obtained from the new design changes prove that a huge amount of cost and injuries were eliminated. The workers line of sight and work ability was also improved through the implementation of the new design technique. The use of this technique automatically adjusts such design variables as angular positions of the limbs, eye level, and trunk. Section 5.9.1 illustrates the old and new design and the rational behind the use of Process 1 in Table 4.1 as a design solution.

5.9.1 DESCRIPTION OF INITIAL AND MODIFIED DESIGN

This section provides the initial design considered for modification, the design recommendation, and the final design.

Initial Design:

The initial design is a work condition that involves the manikin bending at an angle of almost 90º at the waist level to see beneath the assembly. The assembly is placed on a conveyor which is operated manually. On trying to tighten various nuts beneath the assembly, the manikin is subjected to twisting and bending of various body parts such as the arms, the neck, the trunk, and the wrist. This current position was identified with the name, Fred 4.55 in the previous RULA analysis and also shown in Table 5.19. This particular posture is repeated as many as a 100 times daily.

Design Recommendation:

From Process 1 in Table 4.1, the observation column states that "if eye levels is far above or below the view location, use an adjustable stool to improve the field of view". Improving the field of view automatically eliminates twists and bends on the human body segments. Hence, we used Process 1 as a re-design guideline for the particular work condition under observation.

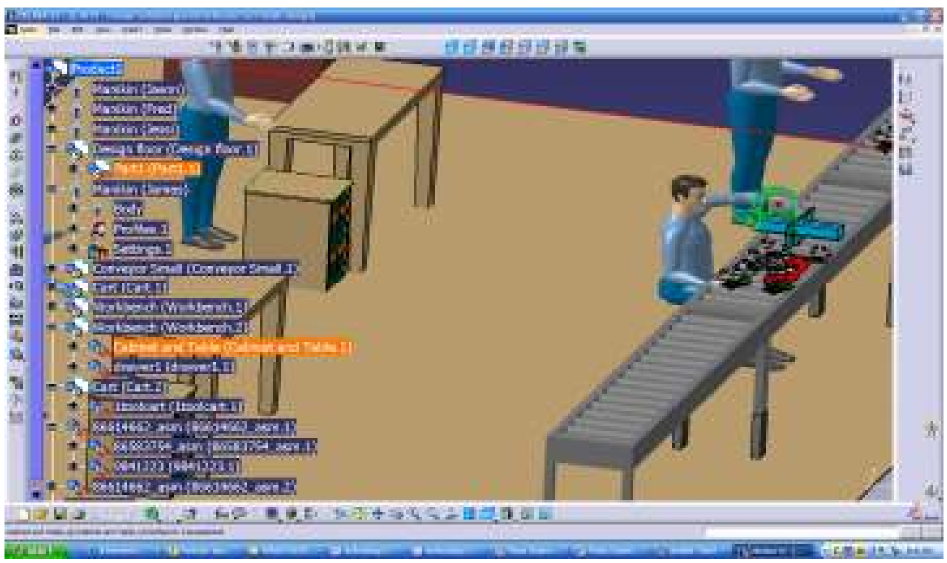

FIG. 5.13: SCREEN CAPTURE OF DELMIA V5© SOFTWARE DURING REDESIGN

Final Design:

As illustrated in Fig. 5.13, the assembly operation was simulated with the assembly line worker in a seated posture. Fig. 5.13 shows the new design recommendation where the worker is in a seated position. This new position eliminated the effects of twists, torsion, bend, and poor field of view which were experienced in the previous standing posture. The height of this stool can be adjusted for different human anthropometric ranges. Fig 5.14 shows the initial posture before re-design and the final posture after re-design.

FIG 5.14: INITIAL POSTURE BEFORE RE-DESIGN AND FINAL POSTURE AFTER RE-DESIGN

Table 5.19 shows the RULA results before and after the design implementation. The results show that a major improvement was achieved by using an adjustable seat to carry out basic tasks that impact excessive stress and strain on the body.

TABLE 5.19: RULA ANALYSIS RESULT BOTH BEFORE AND AFTER REDESIGN

Body part	**INITIAL**		**MODIFIED**	
	Fred 4.55		**Fred 4.55**	
Upper arm	1		1	
Fore arm	3		2	
Wrist	1		1	
Muscle	0		0	
Wrist and arm	3		3	
Neck	6		2	
Trunk	5		2	
Leg	1		1	
Neck, trunk, & leg	0		3	
Final score	**5**		**3**	
Cost	**$10,509**		**$152.63**	98.55% cost reduction

5.9.2 Cost Savings Due To Re-Design

In general, the estimated cost of a basic adjustable stool is $150.00. From the analysis presented in Table 5.19, the injury cost based on the previous analysis is $10,509.18 while the injury cost associated with the current re-design is $152.64. Hence, we realized a savings of $10,356.54 ($10,509.18 - ($152.64+$150) ≈ $10,200.00) and hence a 98.5% reduction in injury cost. In as much as there is no scientific proof to show the exact frame of time within which these costs could be saved, we anticipate a time frame between 2 weeks to 2 years. However, a plant with a low injury record may experience a cost savings lower than that obtained through this analysis. Conclusively, human safety is improved through the implementation of basic rules of thumb in the design phase.

Fig. 5.15 presents the cost implications of the re-design. The green bar shows the cost of the previous posture and the yellow bar shows the cost of the current design. Specific comparisons are conducted on the forearm, neck, trunk, and neck/trunk/leg.

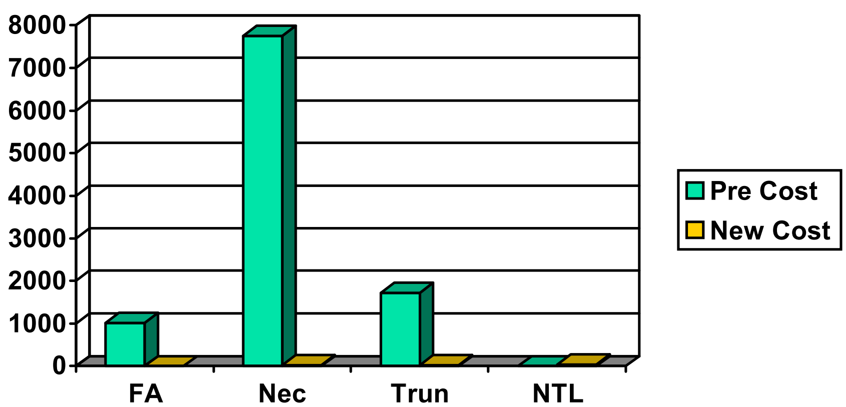

Fig. 5.15: Design Savings: Body Part

5.10 Summary

The various results obtained from this analysis are based on the assembly line in Chapter 3. The results obtained from the RULA analysis show that out of the 14 postures analyzed, only one of them is acceptable from RULA point of view. Table

5.20 shows the basic summary of the postural scores obtained from the RULA analysis while Table 5.5 shows the number of postures associated with various scores. The results also show that the lift operation studied is unsafe while the push-pull and carry operations are acceptable.

Table 4.1 provides various rules of thumb for both lifting and carrying operations. The results of the biomechanical single action analysis provide numerical evidence of some of the claims made through the RULA analysis. Some postures show a higher L4-L5 compression than other while some postures show a higher L4-L5 moment, body load compression, and axial twist compression. The summary of this analysis is presented in Table 5.10.

The cost analysis provided an estimate of the injury cost expectations. However, this analysis of cost also provides a general idea on the assembly cells or body parts at risk of repetitive injuries. The body part cost analysis illustrated in Fig. 5.7 shows that in all the analysis conducted, the muscles experience the highest risk followed by the multiple body parts, neck, and trunk respectively. Also, the costs obtained from the assembly line analysis shows the various body parts subjected to risks of repetitive injuries.

The result of the re-design conducted on a sample posture in the example system of Chapter 3 also shows in Fig. 5.14 a huge savings in injury costs for different body parts. The final analysis conducted on the previous and final postures after re-design show a 98.55% reduction in injury costs for the particular posture considered in the assembly system of Chapter 3. It can also be seen from Fig. 5.13 the huge savings in cost and the same procedure can be applied to different cells to achieve similar results and cost savings.

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CHAPTER 6: SUMMARY, CONCLUSIONS, AND FUTURE WORK

6.1 OVERVIEW

The main objectives of this thesis discussed in Section 1.3 were achieved in this study. The following are the objectives previously listed in Section 1.3:

1. To develop a general methodology for analysis of work injuries given an assembly line. The general methodology includes a specification of information that needs to be collected, the processing of information to lead to the results that are related to work injury levels, and the corresponding costs.
2. To study preliminary methodologies for synthesis, especially re-design of an assembly for the purpose of work injury reduction.
3. To apply the methodologies developed in Objective 1 and Objective 2 to a real assembly line in order to demonstrate how the methodologies are used. This will also provide a complete evaluation of the injury situation for this assembly line with an aim to improve the design while reducing work injury and cost.

With respect to Objective 1, an integrated approach to the work injury analysis for an assembly line was developed in Chapter 4. The example system presented in Chapter 3 was used to explain the methodology. The methodology has covered the following components: (1) information to be collected and the means of collection, (2) the data format of the collected information, and (3) the interpretation of the result generated from a computer aided software program. The results include the work injury type and level and the cost that can be incurred using injury cost information from SWCB.

With respect to Objective 2, a simple empirical-based method was developed and with Table 5.19 presenting the results of both the good and bad designs in terms of the work injury levels. The effectiveness of this method was shown through the application on a critical work posture in the example system of Chapter 3. It was shown that there is a high potential for possible reduction in work injury cost. With respect to Objective 3, the comprehensive analysis and synthesis of the example system was performed in Chapter 5, which has generated a complete set of results regarding the work injury type and level as well as the cost. The results were further used to initiate a re-design as proof of possible injury reduction.

6.2 Conclusions

The following are the conclusions of this research:

1. The biomechanical models in modeling and simulation software packages such as Delmia V5© can be used to successfully establish a relationship between a work activity and its associated work injuries and costs.
2. A science-based approach for addressing assembly line work injuries is both efficient and cost effective.
3. The analysis of human interactions in an assembly line can be used to understand the various forces, stresses, and strain on the body and the possible relationship between these factors and injury levels.
4. SWCB injury database effectively provides valid scientific information for various research studies related to cost of repetitive activities.
5. For the example assembly line system, the cost of the work injury for the 6 work Cells studied is an expected ≈ $28,000.00, which could be incurred by the companies' management between 2 weeks to 2 years.

Note: These costs may vary depending on such factors as the injury potential of the work Cells being studied and the number of work Cells studied.

6.3 Contributions

The following are some of the major contributions made through this study:

(1.) Proposed a general methodology by integrating various methods used for ergonomic design consideration. The general methodology includes the specification of input parameters, procedures for efficient execution of commercially available software, and interpretation of results. The methodology also includes the injury cost analysis procedures. This implies that with this methodology, the cost of work injuries in a specific assembly line can be calculated.

(2.) Studied an existing assembly line using the proposed methodology which then resulted in a list of meaningful recommendations on the assembly line while considering the current injury levels and their possible impact on cost.

(3.) Proposed a unique technique used to import Pro-E Wildfire 2 assembly models into Delmia V5© software, which helped achieve the integration of various assembly processes starting from data collection to the final estimate of injury costs. This technique was earlier discussed in the methodology.

(4.) Proposed a set of rules that can be used to guide the re-design of an assembly line. These rules are aimed at reducing or possibly eliminating repetitive injuries and their associated costs, and also implemented the use of this technique to prove the possibility of reducing injuries and its associated costs using the rule of thumb technique.

6.4 Recommendations And Discussion

Various limitations were observed in this work. These are identified and presented in this section for future reference and possible improvements.

1. Implementation Of NIOSH Algorithm

Following the equations formulated in the revised NIOSH equation (NIOSH 1991), there is a need for further research aimed at modifying these equations. Previous experimental analyses have verified the influence of age and population in performance rating. The current NIOSH equation has no factor to identify for the age or population of the operator. The Delmia V5© software has also incorporated the NIOSH 1991 and 1981 equations which need to be modified for more authentic scientific results. However, further investigation of the NIOSH equation or other relevant equations such as Comprehensive lifting models needs to be studied, improved, and incorporated into ergonomic software packages.

2. Possible Improvement of RULA

From basic observation on the results obtained from Delmia V5©, the RULA analysis broke down the body segments and parts into non-distinct parts. That is to say, some of the parts are not identifiable in the SWCB database. Some of these parts are the Posture A and the Posture B. It would be nice if the RULA analysis can break down the body groups into more identifiable parts. This will surely improve the results obtained from the cost analysis. Also, the RULA chart studied in the analytical approach has no population and percentile included in the chart. The reason behind this is unknown. However, the points of pain on the human body may not be dependent on just the deviations from normal postural angles as can be seen in the RULA body angle threshold values in B4. This may also involve factors such as strength, population, and percentile. The Delmia V5© has incorporated human percentile and population in its RULA score. However, this option may only be available for the biomechanical model approach and not the analytical approach described in Chapter 4.

3. Incorporating A Wider Range Of Repetition In Experiments

In most current ergonomic software packages analyzed, repetivity is given 3 levels. This can be classified as less repetitive, least repetitive, and most repetitive. In actual production environments, repetivity has a wider range of values up to infinity.

However, considering an 8hr work day, 5 days a week, repetivity can be given numerical values if further experiments in this area can be conducted. These values can be obtained through experimental analyses while considering different anthropometric ranges and age. The reason is that the number of repetitions for any activity is one of the important factors that determine whether repetitive injuries will occur or not. This factor deserves to be considered as one of the main factors of interest just as weight. If experiments can be conducted to evaluate the changes in some existing parameters with respect to a wider range of repetivity, the results would need to be incorporated in the Ergonomics software.

4. MOTION TRACKING SYSTEM

Also, further study needs to be conducted in the motion tracking system. This system currently has the key to several problems being faced in the area of modeling and simulation as the human motion is captured real time. This motion tracking system also has a plug in that allows users to connect to the Delmia V5© software. However, various limitations occur with the motion tracking system. Firstly, using the motion tracking system in the actual production environment (production plant) will be so costly that the need may not be justified. This may involve dismantling the 8 cameras from one work cell to another. However, this activity needs to be carried out by experts and the eight (8) cameras as shown in C1 need to be synchronized. Also, the motion tracker can only track motion within a limited space. Such activities as pushing, pulling, walking, and running may never be tracked using this system. There is also need to attach sensors on objects. This will also pose a problem as real production environments will always have obstacles making it difficult to view some of these attached sensors.

The motion tracking system seems to be a more realistic method when used in a virtual work environment e.g. a research lab. However, there is need for the human subjects to mimic the exact assembly activity. Calibration of the work environment when using the motion tracking system requires some expertise. Actual components used in the line may be required to obtain a more realistic posture and hence, an accurate result. The availability of the actual assembly components may not be too necessary if the subject is a good actor. But for usability reasons, space optimization and reach, there is a need to attach sensors to the actual equipments used in the plant in order to obtain the exact manikin posture.

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APPENDIX A: DETAILED RESULTS ON BIOMECHANICAL SINGLE ACTION ANALYSES

A1: RESULTS INCLUDE SUMMARY DATA, GROUND REACTIONS, JOINT MOMENT STRENGTH DATA, REACTION FORCES, AND SEGMENT POSITIONS

This section presents a more detailed result obtained from the biomechanical single action analysis which was conducted on the assembly system of Chapter 3. These results are presented for each of the 15 postures analyzed in the plant. The various values presented in the tables cannot be used solely to identify if injuries will occur or not. These values are more useful when compared with similar postures and their results.

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SUMMARY DATA TAB

Analyses	Value
L4-L5 Moment (N_m)	12
L4-L5 Compression (N)	775
Body Load Compression (N)	439
Axial Twist Compression (N)	1
Flex/Ext Compression (N)	200
L4-L5 Joint Shear (N)	21 Posterior
Abdominal Force (N)	0
Abdominal Pressure (N_m2)	0

GROUND REACTION (N)

Total (X)	0
Total (Y)	0
Total (Z)	819
Left Foot (X)	0
Left Foot (Y)	0
Left Foot (Z)	409
Right Foot (X)	0
Right Foot (Y)	0
Right Foot (Z)	409

SPINE LIMIT DATA TAB

Forces	Value (N)
Compression Limits	775
Joint Shear Limits	21 Posterior

JOINT MOMENT STRENGTH DATA TAB

Joint	DOF	Moment (N_m)	% Pop.	Not Capable	Mean (N_m)	Reference
Right Elbow	Flexion-Extension	2 Flexion	0.0	71	15	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	9	2	Askew, An, Morrey and Chao (1987)
Left Elbow	Flexion-Extension	3 Flexion	0.0	71	15	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	9	2	Askew, An, Morrey and Chao (1987)
Right Shoulder	Flexion-Extension	5 Flexion	0.0	69	14	Koski and McGill (1994)
	Abduction-Adduction	0	0.0	72	28	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Internal-external rotation	1 Ext. Rotation	DNA	DNA	DNA	DNA
Left Shoulder	Flexion-Extension	4 Flexion	0.0	90	20	Koski and McGill (1994)
	Abduction-Adduction	0	DNA	DNA	DNA	DNA

	Internal-external rotation	1 Ext. Rotation	DNA	DNA	DNA	DNA
Lumbar (L4-L5)	Flexion-Extension	12 Extension	0.0	369	69	Troup and Chapman (1969)
	Right-left lateral bend	7 Left Lateral Bend	0.0	148	40	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)
	Right-left twist	0	0.0	74	23	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)

REACTION FORCES DATA TAB

Segment	Proximal Force(N)	Distal Force(N)	Proximal Moment(N_m)	Distal Moment(N_m)
Right Foot				
X	0	0	0	0
Y	0	0	-8	0
Z	-398	0	0	0
Right Leg				
X	0	0	0	0
Y	0	0	-8	8
Z	-359	398	0	0
Right Thigh				
X	0	0	0	0
Y	0	0	-8	8
Z	-278	359	0	0
Left Foot				
X	0	0	0	0
Y	0	0	-8	0
Z	-398	0	0	0
Left Leg				
X	0	0	0	0

Y	0	0	-8	8
Z	-359	398	0	0
Left Thigh				
X	0	0	0	0
Y	0	0	-8	8
Z	-278	359	0	0
Right Hand				
X	0	0	0	0
Y	0	0	0	0
Z	5	0	0	0
Right Forearm				
X	0	0	1	0
Y	0	0	2	0
Z	18	-5	0	0
Right Arm				
X	0	0	-3	-1
Y	0	0	4	-2
Z	41	-18	0	0
Left Hand				
X	0	0	0	0
Y	0	0	0	0
Z	5	0	0	0
Left Forearm				
X	0	0	-2	0
Y	0	0	2	0
Z	18	-5	0	0
Left Arm				
X	0	0	-1	2
Y	0	0	4	-2
Z	41	-18	0	0
Head-Neck				
X	0	0	-1	0
Y	0	0	3	0
Z	66	0	0	0
Pelvis				
X	0	0	-7	7
Y	0	0	15	-12
Z	555	-439	0	0
Trunk				
X	0	0	-7	5

Y	0	0	12	-12
Z	439	-148	0	0

SEGMENT POSITIONS TAB

Segment Proximal Coordinates (in)	Proximal Coordinates (in)	Distal Coordinates (in)	XY plane angle (deg)	YZ plane angle (deg)	Center of gravity coordinates (in)	Length (in)
Right Foot	(0.000 , 19.172 , 3.195)	(4.973 , 19.172 , 1.515)	-18.7	-90.0	(2.486 , 19.172 , 2.355)	5.249
Right Leg	(0.000 , 19.172 , 19.654)	(0.000 , 19.172 , 3.195)	-90.0	-90.0	(0.000 , 19.172 , 12.527)	16.459
Right Thigh	(0.000 , 19.172 , 36.957)	(0.000 , 19.172 , 19.654)	-90.0	-90.0	(0.000 , 19.172 , 29.465)	17.303
Left Foot	(0.000 , 26.195 , 3.195)	(4.973 , 26.195 , 1.515)	-18.7	-90.0	(2.486 , 26.195 , 2.355)	5.249
Left Leg	(0.000 , 26.195 , 19.654)	(0.000 , 26.195 , 3.195)	-90.0	-90.0	(0.000 , 26.195 , 12.527)	16.459
Left Thigh	(0.000 , 26.195 , 36.957)	(0.000 , 26.195 , 19.654)	-90.0	-90.0	(0.000 , 26.195 , 29.465)	17.303
Right Hand	(8.531 , 14.803 , 52.949)	(11.924 , 16.203 , 54.428)	23.6	133.4	(10.248 , 15.512 , 53.697)	3.957
Right Forearm	(1.611 , 12.258 , 46.056)	(8.531 , 14.803 , 52.949)	44.9	110.3	(4.586 , 13.352 , 49.020)	10.094
Right Arm	(-1.499 , 17.272 , 56.490)	(1.611 , 12.258 , 46.056)	-73.4	-64.3	(-0.143 , 15.086 , 51.940)	11.986
Left Hand	(11.553 , 21.645 , 41.954)	(13.780 , 18.375 , 41.983)	0.7	0.5	(12.680 , 19.991 , 41.969)	3.957
Left Forearm	(5.333 , 29.319 , 44.030)	(11.553 , 21.645 , 41.954)	-18.5	-15.1	(8.007 , 26.020 , 43.138)	10.094
Left Arm	(2.418 , 27.470 , 55.509)	(5.333 , 29.319 , 44.030)	-75.8	-99.2	(3.689 , 28.276 , 50.504)	11.986
Head-Neck	(0.139 , 22.548 , 59.945)	(2.180 , 21.981 , 65.084)	68.3	83.7	(2.180 , 21.981 , 65.084)	5.559
Pelvis	(0.000 , 22.683 , 36.957)	(0.262 , 22.685 , 42.603)	87.3	90.0	(0.094 , 22.684 , 38.990)	5.651
Trunk	(0.262 , 22.685 , 42.603)	(0.139 , 22.548 , 59.945)	90.4	89.5	(0.289 , 22.487 , 48.954)	17.343

SUMMARY DATA TAB

Analyses	Value
L4-L5 Moment (N_m)	22
L4-L5 Compression (N)	1863
Body Load Compression (N)	390
Axial Twist Compression (N)	52
Flex/Ext Compression (N)	373
L4-L5 Joint Shear (N)	2 Posterior
Abdominal Force (N)	0
Abdominal Pressure (N_m^2)	0

GROUND REACTION (N)

Total (X)	0
Total (Y)	0
Total (Z)	819
Left Foot (X)	0
Left Foot (Y)	0
Left Foot (Z)	695
Right Foot (X)	0
Right Foot (Y)	0
Right Foot (Z)	124

SPINE LIMIT DATA TAB

Forces	Value (N)
Compression Limits	1863
Joint Shear Limits	2 Posterior

JOINT MOMENT STRENGTH DATA TAB

Joint	DOF	Moment (N_m)	% Pop.	Not Capable	Mean (N_m)	Reference
Right Elbow	Flexion-Extension	1 Flexion	0.0	71	15	Askew, An, Morrey and Chao (1987)
	Supination-	0	0.0	9	2	Askew, An,

	pronation					Morrey and Chao (1987)
Left Elbow	Flexion-Extension	1 Flexion	0.0	71	15	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	9	2	Askew, An, Morrey and Chao (1987)
Right Shoulder	Flexion-Extension	1 Flexion	0.0	69	14	Koski and McGill (1994)
	Abduction-Adduction	5 Abduction	DNA	DNA	DNA	DNA
	Internal-external rotation	0	0.0	27	9	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
Left Shoulder	Flexion-Extension	6 Flexion	0.0	69	14	Koski and McGill (1994)
	Abduction-Adduction	1 Adduction	0.0	72	28	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Internal-external rotation	1 Ext. Rotation	DNA	DNA	DNA	DNA
Lumbar (L4-L5)	Flexion-Extension	22 Extension	0.0	480	93	Troup and Chapman (1969)
	Right-left lateral bend	55 Left Lateral Bend	0.9	148	40	Gomez, P.T., Beach, G.,

						Cooke, C., Hrudey, W., and Goyert, P (1991)
	Right-left twist	7 Left Twist	0.0	74	23	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)

FRED 3.28

SUMMARY DATA TAB

Analyses	Value
L4-L5 Moment (N_m)	11
L4-L5 Compression (N)	1204
Body Load Compression (N)	427
Axial Twist Compression (N)	14
Flex/Ext Compression (N)	185
L4-L5 Joint Shear (N)	5 Posterior
Abdominal Force (N)	0
Abdominal Pressure (N_m^2)	0

GROUND REACTION (N)

Total (X)	0
Total (Y)	0
Total (Z)	819
Left Foot (X)	0
Left Foot (Y)	0
Left Foot (Z)	409
Right Foot (X)	0
Right Foot (Y)	0
Right Foot (Z)	409

SPINE LIMIT DATA TAB

Forces	Value (N)
Compression Limits	1204
Joint Shear Limits	5 Posterior

JOINT MOMENT STRENGTH DATA TAB

Joint	DOF	Moment (N_m)	% Pop.	Not Capable	Mean (N_m)	Reference
Right Elbow	Flexion-Extension	2 Flexion	0.0	71	15	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	9	2	Askew, An, Morrey and Chao (1987)
Left Elbow	Flexion-Extension	2 Flexion	0.0	71	15	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	9	2	Askew, An, Morrey and Chao (1987)
Right Shoulder	Flexion-Extension	1 Extension	0.0	90	20	Koski and McGill (1994)
	Abduction-Adduction	6 Abduction	DNA	DNA	DNA	DNA
	Internal-external rotation	2 Ext. Rotation	DNA	DNA	DNA	DNA
Left Shoulder	Flexion-Extension	1 Extension	0.0	90	20	Koski and McGill (1994)
	Abduction-Adduction	4 Adduction	0.8	72	28	Lannersten, Harms-Ringdahl, Schuldt and

						Ekholm (1993)
	Internal-external rotation	1 Ext. Rotation	0.0	27	9	DNA
Lumbar (L4-L5)	Flexion-Extension	11 Extension	0.0	480	93	Troup and Chapman (1969)
	Right-left lateral bend	30 Left Lateral Bend	0.0	148	40	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)
	Right-left twist	2 Left Twist	0.0	74	23	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)

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SUMMARY DATA TAB

Analyses	Value
L4-L5 Moment (N_m)	32
L4-L5 Compression (N)	1425
Body Load Compression (N)	424
Axial Twist Compression (N)	16
Flex/Ext Compression (N)	540
L4-L5 Joint Shear (N)	54 Anterior
Abdominal Force (N)	2
Abdominal Pressure (N_m^2)	0

GROUND REACTION (N)

Total (X)	0
Total (Y)	0
Total (Z)	819
Left Foot (X)	0
Left Foot (Y)	0
Left Foot (Z)	396
Right Foot (X)	0
Right Foot (Y)	0
Right Foot (Z)	423

SPINE LIMIT DATA TAB

Forces	Value (N)
Compression Limits	1425
Joint Shear Limits	54 Anterior

JOINT MOMENT STRENGTH DATA TAB

Joint	DOF	Moment (N_m)	% Pop.	Not Capable	Mean (N_m)	Reference
Right Elbow	Flexion-Extension	3 Flexion	0.0	71	15	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	9	2	Askew, An, Morrey and Chao (1987)
Left Elbow	Flexion-Extension	3 Flexion	0.0	41	11	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	9	2	Askew, An, Morrey and Chao (1987)
Right Shoulder	Flexion-Extension	4 Flexion	0.0	69	14	Koski and McGill (1994)
	Abduction-	1 Adduction	0.0	72	28	Lannersten,

	Adduction					Harms-Ringdahl, Schuldt and Ekholm (1993)
	Internal-external rotation	1 Ext. Rotation	DNA	DNA	DNA	DNA
Left Shoulder	Flexion-Extension	3 Flexion	0.0	69	14	Koski and McGill (1994)
	Abduction-Adduction	3 Abduction	DNA	DNA	DNA	DNA
	Internal-external rotation	1 Ext. Rotation	DNA	DNA	DNA	DNA
Lumbar (L4-L5)	Flexion-Extension	32 Extension	0.0	480	93	Troup and Chapman (1969)
	Right-left lateral bend	23 Left Lateral Bend	0.0	148	40	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)
	Right-left twist	2 Right Twist	0.0	74	23	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)

SUMMARY DATA TAB

Analyses	**Value**
L4-L5 Moment (N_m)	60
L4-L5 Compression (N)	1505
Body Load Compression (N)	402
Axial Twist Compression (N)	14
Flex/Ext Compression (N)	1007
L4-L5 Joint Shear (N)	87 Anterior
Abdominal Force (N)	0
Abdominal Pressure (N_m^2)	0

GROUND REACTION (N)

Total (X)	0
Total (Y)	0
Total (Z)	819
Left Foot (X)	0
Left Foot (Y)	0
Left Foot (Z)	521
Right Foot (X)	0
Right Foot (Y)	0
Right Foot (Z)	298

SPINE LIMIT DATA TAB

Forces	**Value (N)**
Compression Limits	1505
Joint Shear Limits	87 Anterior

JOINT MOMENT STRENGTH DATA TAB

Joint	**DOF**	**Moment (N_m)**	**% Pop.**	**Not Capable**	**Mean (N_m)**	**Reference**
Right Elbow	Flexion-Extension	2 Flexion	0.0	71	15	Askew, An, Morrey and Chao (1987)

	Supination-pronation	0	0.0	9	2	Askew, An, Morrey and Chao (1987)
Left Elbow	Flexion-Extension	1 Flexion	0.0	71	15	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	9	2	Askew, An, Morrey and Chao (1987)
Right Shoulder	Flexion-Extension	6 Flexion	0.0	69	14	Koski and McGill (1994)
	Abduction-Adduction	2 Abduction	DNA	DNA	DNA	DNA
	Internal-external rotation	2 Ext. Rotation	DNA	DNA	DNA	DNA
Left Shoulder	Flexion-Extension	4 Flexion	0.0	69	14	Koski and McGill (1994)
	Abduction-Adduction	4 Abduction	0.8	72	28	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Internal-external rotation	0	DNA	DNA	DNA	DNA
Lumbar (L4-L5)	Flexion-Extension	Flexion-Extension	60 Extension	0.0	480	Troup and Chapman (1969)
	Right-left lateral bend	4 Left Lateral Bend	0.0	143	40	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W.,

						and Goyert, P (1991)
	Right-left twist	2 Right Twist	0.0	72	20	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)

FRED 4.55

SUMMARY DATA TAB

Analyses	Value
L4-L5 Moment (N_m)	79
L4-L5 Compression (N)	2379
Body Load Compression (N)	278
Axial Twist Compression (N)	43
Flex/Ext Compression (N)	1320
L4-L5 Joint Shear (N)	189 Anterior
Abdominal Force (N)	0
Abdominal Pressure (N_m^2)	0

GROUND REACTION (N)

Total (X)	0
Total (Y)	0
Total (Z)	819
Left Foot (X)	0
Left Foot (Y)	0
Left Foot (Z)	51
Right Foot (X)	0
Right Foot (Y)	0
Right Foot (Z)	768

SPINE LIMIT DATA TAB

Forces	Value (N)
Compression Limits	2379
Joint Shear Limits	189 Anterior

JOINT MOMENT STRENGTH DATA TAB

Joint	DOF	Moment (N_m)	% Pop.	Not Capable	Mean (N_m)	Reference
Right Elbow	Flexion-Extension	3 Flexion	0.0	71	15	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	9	2	Askew, An, Morrey and Chao (1987)
Left Elbow	Flexion-Extension	0	0.0	71	15	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	9	2	Askew, An, Morrey and Chao (1987)
Right Shoulder	Flexion-Extension	0	0.0	90	20	Koski and McGill (1994)
	Abduction-Adduction	4 Abduction	DNA	DNA	DNA	DNA
	Internal-external rotation	0	0.0	27	9	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
Left Shoulder	Flexion-Extension	8 Flexion	0.0	53	13	Lannersten, Harms-Ringdahl, Schuldt and

						Ekholm (1993)
	Abduction-Adduction	1 Abduction	DNA	DNA	DNA	DNA
	Internal-external rotation	1 Ext. Rotation	DNA	DNA	DNA	DNA
Lumbar (L4-L5)	Flexion-Extension	79 Extension	0.0	480	93	Troup and Chapman (1969)
	Right-left lateral bend	38 Left Lateral Bend	0.0	148	40	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)
	Right-left twist	6 Right Twist	0.0	74	23	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)

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SUMMARY DATA TAB

Analyses	**Value**
L4-L5 Moment (N_m)	33
L4-L5 Compression (N)	1685
Body Load Compression (N)	401
Axial Twist Compression (N)	40
Flex/Ext Compression (N)	543
L4-L5 Joint Shear (N)	37 Anterior
Abdominal Force (N)	0
Abdominal Pressure (N_m^2)	0

GROUND REACTION (N)

Total (X)	0
Total (Y)	0
Total (Z)	819
Left Foot (X)	0
Left Foot (Y)	0
Left Foot (Z)	619
Right Foot (X)	0
Right Foot (Y)	0
Right Foot (Z)	200

SPINE LIMIT DATA TAB

Forces	**Value (N)**
Compression Limits	1685
Joint Shear Limits	37 Anterior

JOINT MOMENT STRENGTH DATA TAB

Joint	**DOF**	**Moment (N_m)**	**% Pop.**	**Not Capable**	**Mean (N_m)**	**Reference**
Right Elbow	Flexion-Extension	1 Flexion	0.0	71	15	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	9	2	Askew, An, Morrey and Chao (1987)
Left Elbow	Flexion-Extension	2 Flexion	0.0	71	15	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	9	2	Askew, An, Morrey and Chao (1987)
Right Shoulder	Flexion-Extension	2 Flexion	0.0	69	14	Koski and McGill (1994)
	Abduction-	1 Abduction	DNA	DNA	DNA	DNA

	Adduction					
	Internal-external rotation	0	DNA	DNA	DNA	DNA
Left Shoulder	Flexion-Extension	0	0.0	90	20	Koski and McGill (1994)
	Abduction-Adduction	3 Abduction	0.7	72	28	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Internal-external rotation	1 Ext. Rotation	DNA	DNA	DNA	DNA
Lumbar (L4-L5)	Flexion-Extension	33 Extension	0.0	480	93	Troup and Chapman (1969)
	Right-left lateral bend	36 Left Lateral Bend	0.0	148	40	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)
	Right-left twist	5 Left Twist	0.0	74	23	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)

SUMMARY DATA TAB

Analyses	Value
L4-L5 Moment (N_m)	26
L4-L5 Compression (N)	927
Body Load Compression (N)	369
Axial Twist Compression (N)	9
Flex/Ext Compression (N)	439
L4-L5 Joint Shear (N)	35 Anterior
Abdominal Force (N)	0
Abdominal Pressure (N_m^2)	0

GROUND REACTION (N)

Total (X)	0
Total (Y)	0
Total (Z)	745
Left Foot (X)	0
Left Foot (Y)	0
Left Foot (Z)	373
Right Foot (X)	0
Right Foot (Y)	0
Right Foot (Z)	373

SPINE LIMIT DATA TAB

Forces	Value (N)
Compression Limits	927
Joint Shear Limits	35 Anterior

JOINT MOMENT STRENGTH DATA TAB

Joint	DOF	Moment (N_m)	% Pop.	Not Capable	Mean (N_m)	Reference
Right Elbow	Flexion-Extension	0	0.0	32	8	Askew, An, Morrey and Chao (1987)
	Supination-	0	0.0	4	1	Askew, An,

	pronation					Morrey and Chao (1987)
Left Elbow	Flexion-Extension	2 Flexion	0.0	32	8	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	4	1	Askew, An, Morrey and Chao (1987)
Right Shoulder	Flexion-Extension	1 Flexion	0.0	43	10	Koski and McGill (1994)
	Abduction-Adduction	7 Abduction	DNA	DNA	DNA	DNA
	Internal-external rotation	1 Ext. Rotation	DNA	DNA	DNA	DNA
Left Shoulder	Flexion-Extension	0	0.0	43	10	Koski and McGill (1994)
	Abduction-Adduction	1 Adduction	0.0	31	11	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Internal-external rotation	0	0.0	15	4	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
Lumbar (L4-L5)	Flexion-Extension	26 Extension	0.0	299	65	Troup and Chapman (1969)
	Right-left lateral bend	6 Left Lateral Bend	0.0	75	25	Gomez, P.T., Beach, G.,

						Cooke, C., Hrudey, W., and Goyert, P (1991)
	Right-left twist	1 Right Twist	2.0	34	16	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)

JANE 15.14

SUMMARY DATA TAB

Analyses	**Value**
L4-L5 Moment (N_m)	69
L4-L5 Compression (N)	1394
Body Load Compression (N)	236
Axial Twist Compression (N)	1
Flex/Ext Compression (N)	1153
L4-L5 Joint Shear (N)	148 Anterior
Abdominal Force (N)	0
Abdominal Pressure (N_m^2)	0

GROUND REACTION (N)

Total (X)	0
Total (Y)	0
Total (Z)	679
Left Foot (X)	0
Left Foot (Y)	0
Left Foot (Z)	173
Right Foot (X)	0
Right Foot (Y)	0
Right Foot (Z)	506

SPINE LIMIT DATA TAB

Forces	Value (N)
Compression Limits	1394
Joint Shear Limits	148 Anterior

JOINT MOMENT STRENGTH DATA TAB

Joint	DOF	Moment (N_m)	% Pop.	Not Capable	Mean (N_m)	Reference
Right Elbow	Flexion-Extension	0	0.0	32	8	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	4	1	Askew, An, Morrey and Chao (1987)
Left Elbow	Flexion-Extension	1 Flexion	0.0	32	8	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	4	1	Askew, An, Morrey and Chao (1987)
Right Shoulder	Flexion-Extension	1 Flexion	0.0	32	6	Koski and McGill (1994)
	Abduction-Adduction	1 Adduction	0.0	31	11	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Internal-external rotation	0	0.0	15	4	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)

Left Shoulder	Flexion-Extension	4 Flexion	0.0	32	6	Koski and McGill (1994)
	Abduction-Adduction	1 Adduction	DNA	DNA	DNA	DNA
	Internal-external rotation	0	DNA	DNA	DNA	DNA
Lumbar (L4-L5)	Flexion-Extension	69 Extension	0.0	299	65	Troup and Chapman (1969)
	Right-left lateral bend	0	0.0	75	25	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)
	Right-left twist	0	1.7	34	16	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)

JANE 16.12

SUMMARY DATA TAB

Analyses	**Value**
L4-L5 Moment (N_m)	67
L4-L5 Compression (N)	1547
Body Load Compression (N)	226
Axial Twist Compression (N)	41
Flex/Ext Compression (N)	1122
L4-L5 Joint Shear (N)	160 Anterior
Abdominal Force (N)	0
Abdominal Pressure (N_m^2)	0

GROUND REACTION (N)

Total (X)	0
Total (Y)	0
Total (Z)	679
Left Foot (X)	0
Left Foot (Y)	0
Left Foot (Z)	380
Right Foot (X)	0
Right Foot (Y)	0
Right Foot (Z)	299

SPINE LIMIT DATA TAB

Forces	**Value (N)**
Compression Limits	1547
Joint Shear Limits	160 Anterior

JOINT MOMENT STRENGTH DATA TAB

Joint	DOF	Moment (N_m)	% Pop.	Not Capable	Mean (N_m)	Reference
Right Elbow	Flexion-Extension	0	0.0	20	6	Askew, An, Morrey and Chao (1987)

	Supination-pronation	0	0.0	4	1	Askew, An, Morrey and Chao (1987)
Left Elbow	Flexion-Extension	0	0.0	32	8	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	4	1	Askew, An, Morrey and Chao (1987)
Right Shoulder	Flexion-Extension	2 Extension	0.0	43	10	Koski and McGill (1994)
	Abduction-Adduction	6 Adduction	.0	31	11	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Internal-external rotation	1 Ext. Rotation	0.0	15	4	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
Left Shoulder	Flexion-Extension	2 Flexion	0.0	27	6	Koski and McGill (1994)
	Abduction-Adduction	4 Abduction	DNA	DNA	DNA	DNA
	Internal-external rotation	0	0.0	15	4	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
Lumbar (L4-	Flexion-	67 Extension	0.0	299	65	Troup and

L5)	Extension					Chapman (1969)
	Right-left lateral bend	8 Left Lateral Bend	0.0	80	27	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)
	Right-left twist	5 Right Twist	3.2	38	18	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)

JANE 18.47

SUMMARY DATA TAB

Analyses	Value
L4-L5 Moment (N_m)	65
L4-L5 Compression (N)	1364
Body Load Compression (N)	263
Axial Twist Compression (N)	0
Flex/Ext Compression (N)	1089
L4-L5 Joint Shear (N)	126 Anterior
Abdominal Force (N)	0
Abdominal Pressure (N_m^2)	0

GROUND REACTION (N)

Total (X)	0
Total (Y)	0
Total (Z)	679
Left Foot (X)	0
Left Foot (Y)	0
Left Foot (Z)	367
Right Foot (X)	0

Right Foot (Y)	0
Right Foot (Z)	312

SPINE LIMIT DATA TAB

Forces	**Value (N)**
Compression Limits	1364
Joint Shear Limits	126 Anterior

JOINT MOMENT STRENGTH DATA TAB

Joint	**DOF**	**Moment (N_m)**	**% Pop.**	**Not Capable**	**Mean (N_m)**	**Reference**
Right Elbow	Flexion-Extension	2 Flexion	0.0	32	8	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	4	1	Askew, An, Morrey and Chao (1987)
Left Elbow	Flexion-Extension	2 Flexion	0.0	32	8	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	4	1	Askew, An, Morrey and Chao (1987)
Right Shoulder	Flexion-Extension	4 Flexion	0.0	27	6	Koski and McGill (1994)
	Abduction-Adduction	2 Abduction	0.0	31	11	DNA
	Internal-external rotation	0	0.0	15	4	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)

Left Shoulder	Flexion-Extension	2 Flexion	0.0	32	6	Koski and McGill (1994)
	Abduction-Adduction	0	0.0	31	11	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Internal-external rotation	0	0.0	15	4	DNA
Lumbar (L4-L5)	Flexion-Extension	65 Extension	0.0	299	65	Troup and Chapman (1969)
	Right-left lateral bend	1 Left Lateral Bend	0.0	80	27	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)
	Right-left twist	0	1.7	34	16	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)

JANE 19.23

SUMMARY DATA TAB

Analyses	**Value**
L4-L5 Moment (N_m)	55
L4-L5 Compression (N)	1236
Body Load Compression (N)	294

Axial Twist Compression (N)	4
Flex/Ext Compression (N)	916
L4-L5 Joint Shear (N)	96 Anterior
Abdominal Force (N)	0
Abdominal Pressure (N_m^2)	0

GROUND REACTION (N)

Total (X)	0
Total (Y)	0
Total (Z)	679
Left Foot (X)	0
Left Foot (Y)	0
Left Foot (Z)	340
Right Foot (X)	0
Right Foot (Y)	0
Right Foot (Z)	340

SPINE LIMIT DATA TAB

Forces	**Value (N)**
Compression Limits	1236
Joint Shear Limits	96 Anterior

JOINT MOMENT STRENGTH DATA TAB

Joint	**DOF**	**Moment (N_m)**	**% Pop.**	**Not Capable**	**Mean (N_m)**	**Reference**
Right Elbow	Flexion-Extension	2 Flexion	0.0	32	8	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	4	1	Askew, An, Morrey and Chao (1987)
Left Elbow	Flexion-Extension	2 Flexion	0.0	32	8	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	4	1	Askew, An, Morrey and

						Chao (1987)
Right Shoulder	Flexion-Extension	2 Flexion	0.0	32	6	Koski and McGill (1994)
	Abduction-Adduction	1 Adduction	0.0	31	11	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Internal-external rotation	1 Ext. Rotation	0.0	15	4	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
Left Shoulder	Flexion-Extension	5 Flexion	0.0	32	8	Koski and McGill (1994)
	Abduction-Adduction	0	DNA	DNA	DNA	DNA
	Internal-external rotation	1 Ext. Rotation	0.0	15	4	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
Lumbar (L4-L5)	Flexion-Extension	55 Extension	0.0	299	65	Troup and Chapman (1969)
	Right-left lateral bend	1 Right Lateral Bend	0.0	75	25	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W.,

						and Goyert, P (1991)
	Right-left twist	1 Left Twist	1.7	38	18	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)

JANE 20.00

SUMMARY DATA TAB

Analyses	Value
L4-L5 Moment (N_m)	49
L4-L5 Compression (N)	1481
Body Load Compression (N)	264
Axial Twist Compression (N)	13
Flex/Ext Compression (N)	817
L4-L5 Joint Shear (N)	130 Anterior
Abdominal Force (N)	0
Abdominal Pressure (N_m^2)	0

GROUND REACTION (N)

Total (X)	0
Total (Y)	0
Total (Z)	679
Left Foot (X)	0
Left Foot (Y)	0
Left Foot (Z)	220
Right Foot (X)	0
Right Foot (Y)	0
Right Foot (Z)	459

SPINE LIMIT DATA TAB

Forces	**Value (N)**
Compression Limits	1481
Joint Shear Limits	130 Anterior

JOINT MOMENT STRENGTH DATA TAB

Joint	DOF	Moment (N_m)	% Pop.	Not Capable	Mean (N_m)	Reference
Right Elbow	Flexion-Extension	0	0.0	20	6	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	4	1	Askew, An, Morrey and Chao (1987)
Left Elbow	Flexion-Extension	2 Flexion	0.0	32	8	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	4	1	Askew, An, Morrey and Chao (1987)
Right Shoulder	Flexion-Extension	1 Extension	0.0	32	6	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Abduction-Adduction	2 Abduction	DNA	DNA	DNA	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Internal-external	0	0.0	15	4	Lannersten, Harms-

	rotation					Ringdahl, Schuldt and Ekholm (1993)
Left Shoulder	Flexion-Extension	3 Extension	0.0	43	10	Koski and McGill (1994)
	Abduction-Adduction	2 Abduction	0.0	31	11	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Internal-external rotation	1 Ext. Rotation	0.0	15	4	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
Lumbar (L4-L5)	Flexion-Extension	49 Extension	0.0	299	65	Troup and Chapman (1969)
	Right-left lateral bend	20 Left Lateral Bend	1.2	80	27	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)
	Right-left twist	2 Left Twist	2.0	38	18	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)

SUMMARY DATA TAB

Analyses	Value
L4-L5 Moment (N_m)	3
L4-L5 Compression (N)	433
Body Load Compression (N)	343
Axial Twist Compression (N)	1
Flex/Ext Compression (N)	43
L4-L5 Joint Shear (N)	23 Posterior
Abdominal Force (N)	0
Abdominal Pressure (N_m^2)	0

GROUND REACTION (N)

Total (X)	0
Total (Y)	0
Total (Z)	679
Left Foot (X)	0
Left Foot (Y)	0
Left Foot (Z)	340
Right Foot (X)	0
Right Foot (Y)	0
Right Foot (Z)	340

SPINE LIMIT DATA TAB

Forces	Value (N)
Compression Limits	433
Joint Shear Limits	23 Posterior

JOINT MOMENT STRENGTH DATA TAB

Joint	DOF	Moment (N_m)	% Pop.	Not Capable	Mean (N_m)	Reference
Right Elbow	Flexion-Extension	2 Flexion	0.0	32	8	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	4	1	Askew, An, Morrey and

						Chao (1987)
Left Elbow	Flexion-Extension	2 Flexion	0.0	32	8	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	4	1	Askew, An, Morrey and Chao (1987)
Right Shoulder	Flexion-Extension	1 Flexion	0.0	43	10	Koski and McGill (1994)
	Abduction-Adduction	3 Adduction	DNA	DNA	DNA	DNA
	Internal-external rotation	1 Ext. Rotation	0.0	15	4	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
Left Shoulder	Flexion-Extension	3 Flexion	0.0	43	10	Koski and McGill (1994)
	Abduction-Adduction	0	DNA	DNA	DNA	DNA
	Internal-external rotation	1 Ext. Rotation	DNA	DNA	DNA	DNA
Lumbar (L4-L5)	Flexion-Extension	3 Extension	0.0	213	50	Troup and Chapman (1969)
	Right-left lateral bend	2 Left Lateral Bend	0.0	75	25	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)
	Right-left	0	1.7	34	16	Gomez, P.T.,

	twist					Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)

JANE 23.58

SUMMARY DATA TAB

Analyses	Value
L4-L5 Moment (N_m)	81
L4-L5 Compression (N)	1587
Body Load Compression (N)	236
Axial Twist Compression (N)	0
Flex/Ext Compression (N)	1350
L4-L5 Joint Shear (N)	130 Anterior
Abdominal Force (N)	0
Abdominal Pressure (N_m^2)	0

GROUND REACTION (N)

Total (X)	0
Total (Y)	0
Total (Z)	679
Left Foot (X)	0
Left Foot (Y)	0
Left Foot (Z)	316
Right Foot (X)	0
Right Foot (Y)	0
Right Foot (Z)	363

SPINE LIMIT DATA TAB

Forces	Value (N)
Compression Limits	1587
Joint Shear Limits	130 Anterior

JOINT MOMENT STRENGTH DATA TAB

Joint	DOF	Moment (N_m)	% Pop.	Not Capable	Mean (N_m)	Reference
Right Elbow	Flexion-Extension	2 Flexion	0.0	32	8	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	4	1	Askew, An, Morrey and Chao (1987)
Left Elbow	Flexion-Extension	2 Flexion	0.0	32	8	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	4	1	Askew, An, Morrey and Chao (1987)
Right Shoulder	Flexion-Extension	6 Flexion	0.0	27	6	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Abduction-Adduction	3 Abduction	0.0	31	11	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Internal-external rotation	0	0.0	15	4	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
Left Shoulder	Flexion-Extension	6 Flexion	.0	27	6	Koski and McGill

						(1994)
	Abduction-Adduction	3 Abduction	0.0	31	11	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Internal-external rotation	0	0.0	15	4	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
Lumbar (L4-L5)	Flexion-Extension	81 Extension	0.0	299	65	Troup and Chapman (1969)
	Right-left lateral bend	0	0.0	75	25	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)
	Right-left twist	0	1.7	34	16	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)

APPENDIX B: RULA AND SOME DELMIA V5 BODY PART RANGE

B1: RULA WORK SHEET

A worksheet used for upper limb assessment. This worksheet will be applicable if the analytical technique was used in injury assessment. CAD software's employ the basic principles behind the application of this sheet in their software environment.

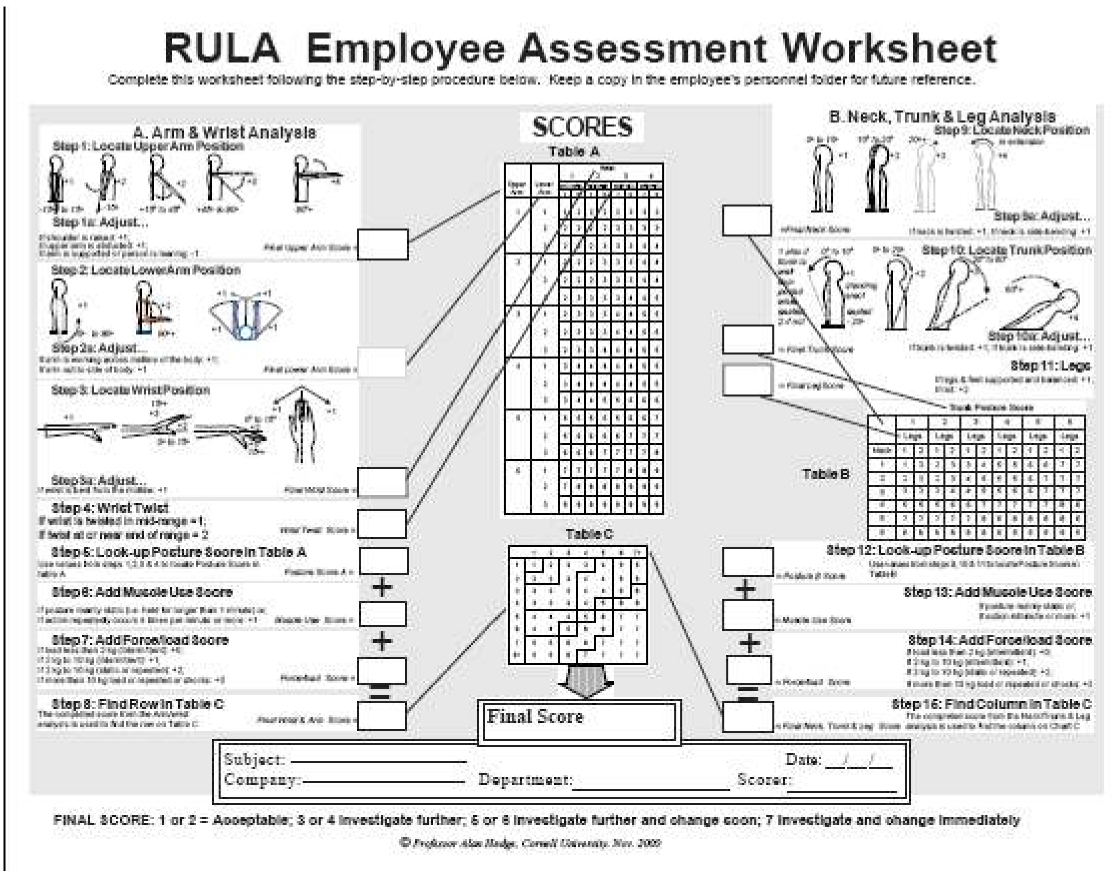


FIG. B1: RULA ASSESSMENT WORK SHEET USED IN ANALYTICAL APPROACH

B2: COLOR ASSOCIATED TO VARIOUS SCORES IN DELMIA V5©

Table Bs shows the exact classification range provided in DELMIA V5© manual. This does not address some other body parts considered in the DELMIA V5© software environment. Hence, Table B3 to generated to address the entire body parts considered in the DELMIA V5© software environment.

TABLE B2: COLOR ASSOCIATIONS TO SCORES (Delmia V5© manual, 2005)

Segment	**Score Range**	**Color associated to the scores**					
		1	**2**	**3**	**4**	**5**	**6**
Upper arm	**1 to 6**						
Forearm	**1 to 3**						
Wrist	**1 to 4**						
Wrist twist	**1 to 2**						
Neck	**1 to 6**						
Trunk	**1 to 6**						

B3: EXTENDED CLASSIFICATION FOR BODY PARTS IN DELMIA V5©

Table B3 presents a more detailed range of scores for all the body part generated by the Delmia V5© results. The sections were obtained through a detailed analysis of the results obtained from the Delmia V5© program.

TABLE B3: EXTENDED CLASSIFICATION FOR BODY PARTS IN DELMIA V5©

Segment	Score Range	Color associated to the score						
		1	2	3	4	5	6	7
Upper arm	1 to 6	Green	Green	Yellow	Yellow	Red	Red	Grey
Forearm	1 to 3	Green	Yellow	Orange	Grey	Grey	Grey	Grey
Wrist	1 to 4	Green	Yellow	Orange	Orange	Grey	Grey	Grey
Wrist twist	1 to 2	Green	Orange	Grey	Grey	Grey	Grey	Grey
Posture A	1 to 7	Green	Green	Green	Yellow	Orange	Orange	Red
Muscle	0 to 1	Red	Grey	Grey	Grey	Grey	Grey	Grey
Force/Load	1 to 7	Yellow	Orange	Orange	Red	Grey	Grey	Grey
Wrist/ Arm	1 to 7	Green	Green	Yellow	Yellow	Orange	Orange	Red
Neck	1 to 6	Green	Green	Yellow	Yellow	Red	Red	Grey
Trunk	1 to 6	Green	Green	Yellow	Yellow	Red	Red	Grey
Leg	1 to 7	Green	Yellow	Orange	Red	Grey	Grey	Grey
Posture B	1 to 7	Green	Green	Green	Yellow	Yellow	Yellow	Orange
Neck, Trunk Leg	1 to 7	Green	Green	Yellow	Yellow	Orange	Orange	Red

NOTE: THE GREY COLORED REGIONS REPRESENT BLANK REGIONS THAT ARE OUT OF RANGE

B4: THRESHOLD VALUES FOR DIFFERENT BODY ANGLES

Table B4 presents the various threshold values associated with the RULA results.

TABLE B4: THRESHOLD VALUES FOR DIFFERENT BODY ANGLES

BODY PART	**THRESHOLD VALUE IN DEGREES**
Shoulder elevation threshold	9.25deg
Upper arm abduction threshold	17.94deg
Arm rotation threshold	20.60deg
Wrist deviation threshold	8.60deg
Wrist twist threshold	0.152deg
Neck twist threshold	5.25deg
Neck side bending threshold	1.05deg
Trunk twist threshold	0.79deg
Trunk side bending threshold	1.05deg

APPENDIX C: MOTION TRACKING

C1: MOTION TRACKING CAMERAS

Fig. C1 shows the eight cameras associated with the motion tracking system. These cameras track the markers placed on the human body while carrying out various operations within the motion tracking work space.

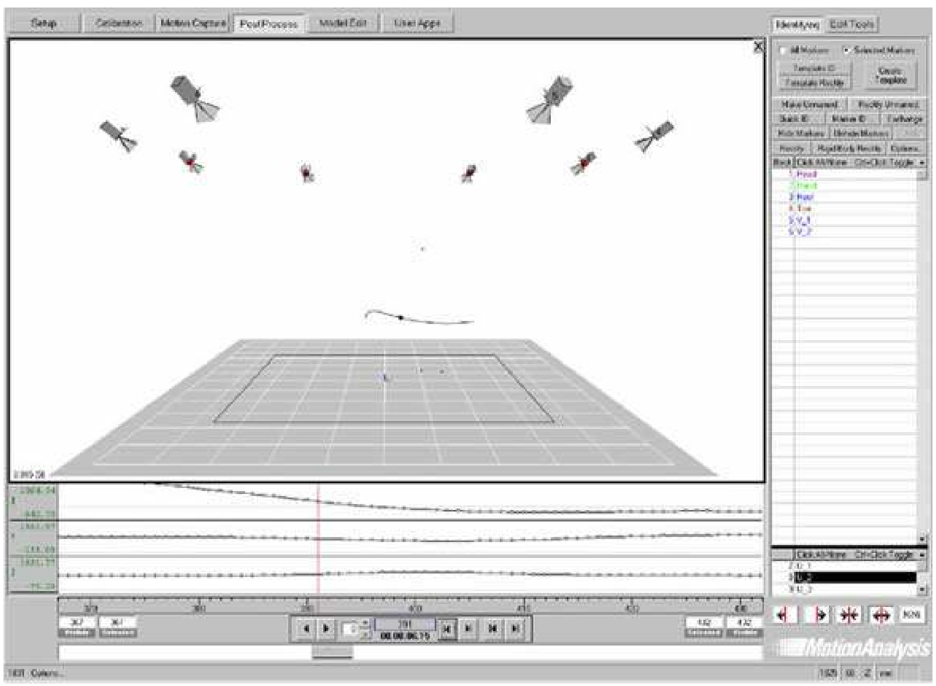
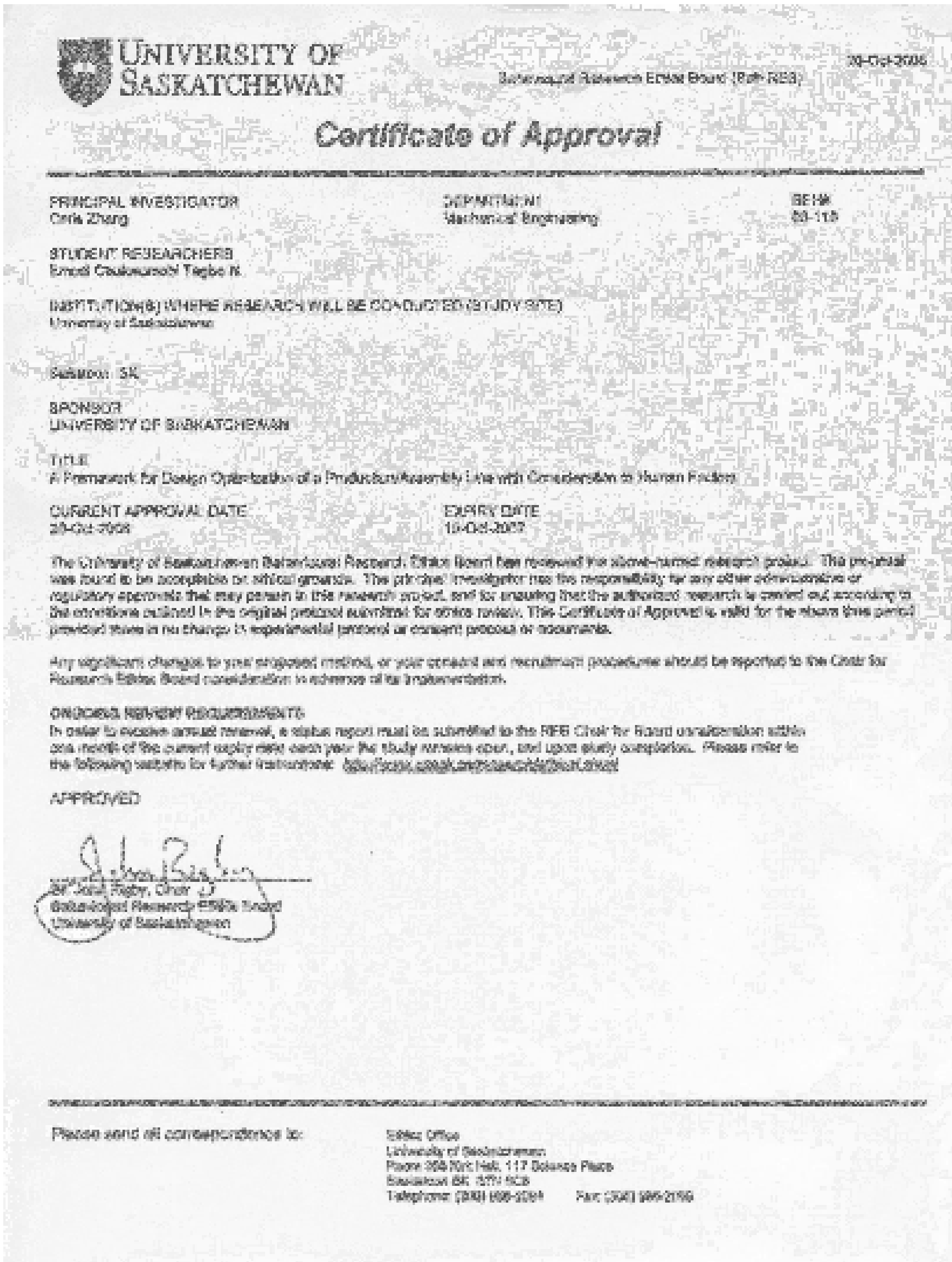


FIG. C1: EIGHT MOTION TRACKING CAMERAS (Evart, 2004)

APPENDIX D: ETHICS APPROVAL

D1 SHOWS THE APPROVAL BY THE ETHICS BOARD FOR HUMAN CENTERED RESEARCH



UNIVERSITY OF SASKATCHEWAN

Behavioural Research Ethics Board (Beh-REB)

20-Oct-2006

Certificate of Approval

PRINCIPAL INVESTIGATOR
Chris Zhang

DEPARTMENT
Mechanical Engineering

BEH#
06-115

STUDENT RESEARCHERS
[illegible] Tegbe N.

INSTITUTION(S) WHERE RESEARCH WILL BE CONDUCTED (STUDY SITE)
University of Saskatchewan

Saskatoon SK

SPONSOR
UNIVERSITY OF SASKATCHEWAN

TITLE
A Framework for Design Optimization of a Production/Assembly Line with Consideration to Human Factors

CURRENT APPROVAL DATE
20-Oct-2006

EXPIRY DATE
19-Oct-2007

The University of Saskatchewan Behavioural Research Ethics Board has reviewed the above-named research project. The proposal was found to be acceptable on ethical grounds. The principal investigator has the responsibility for any other administrative or regulatory approvals that may pertain to this research project, and for ensuring that the authorized research is carried out according to the conditions outlined in the original protocol submitted for ethics review. This Certificate of Approval is valid for the above time period provided there is no change in experimental protocol or consent process or documents.

Any significant changes to your proposed method, or your consent and recruitment procedures should be reported to the Chair for Research Ethics Board consideration in advance of its implementation.

ONGOING REVIEW REQUIREMENTS
In order to receive annual renewal, a status report must be submitted to the REB Chair for Board consideration within one month of the current expiry date each year the study remains open, and upon study completion. Please refer to the following website for further instructions: [illegible]

APPROVED

Dr. John Rigby, Chair
Behavioural Research Ethics Board
University of Saskatchewan

Please send all correspondence to:

Ethics Office
University of Saskatchewan
Room 306 Kirk Hall, 117 Science Place
Saskatoon SK S7N 5C8
Telephone: (306) [illegible] Fax: (306) [illegible]

FIG. D1: ETHICS APPROVAL